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THE PREDICTION OF PORPOISING INCEPTION FOR MODERN PLANING CRAFT

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13. ABSTRACT (Maximum 200 words) The purpose of this project was to study porpoising, one of the most common forms of dynamic instability found in planing boats. In descriptive terms, it is a coupled oscillation in pitch and heave that occurs in relatively calm water. These oscillations can be divergent in amplitude, leading to loss of control, injury to occupants or damage to the craft. The mechanics of porpoising have been studied sporadically from theoretical and experimental perspectives for many years. Studies have shown that the inception of porpoising is influenced by displacement, center of gravity location, and various hull characteristics such as deadrise and beam. Until now, Day & Haag's thesis provided the only systematic test results concerning the porpoising stability limits of planing craft. Although the Day and Haag model tests were brilliantly executed and thoroughly reported, many users of these data are not aware of the size of the models tested. The average beam of the three tiny prismatic hulls was only 3.8 inches. As a starting point, these tests were recreated using a series of three hard-chined prismatic planning hullforms approximately five times larger. The tests included hulls with higher deadrise angles, more typical of craft now employed for high-speed military purposes. Two models of actual full-scale craft, complete with performance-enhancing features including lifting strakes, trim tabs, and variable drive angle were tested. These additions were found to have a profound effect upon the conditions at the inception of porpoising. Established planing hull analysis methods were augmented with techniques developed during the course of the study to provide a basis from which to design and outfit high-speed, heavily laden planing hulls with respect to porpoising stability.

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THE PREDICTION OF PORPOISING INCEPTION FOR MODERN PLANING CRAFT

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Abstract

The purpose of this project was to study porpoising, one of the most common forms of dynamic instability found in planing boats. In descriptive terms, it is a coupled oscillation in pitch and heave that occurs in relatively calm water. These oscillations can be divergent in amplitude, leading to loss of control, injury to occupants or damage to the craft.

The mechanics of porpoising have been studied sporadically from theoretical and experimental perspectives for many years. Studies by Perring (1933), Savitsky (1950 through 1976), Day and Haag (1952), Martin (1978), and others have shown that the inception of porpoising is influenced by displacement, center of gravity location, and various hull characteristics such as deadrise and beam.

Until now, Day & Haag's thesis provided the only systematic test results concerning the porpoising stability limits of planing craft. Although the Day and Haag model tests were brilliantly executed and thoroughly reported, many users of these data are not aware of the size of the models tested. The average beam of the three tiny prismatic hulls was only 3.8 inches. As a starting point, these tests were re-created using a series of three hard-chined prismatic planing hullforms approximately five times larger. The tests included hulls with higher deadrise angles, more typical of craft now employed for high-speed military purposes. Two models of actual full-scale craft, complete with performance-enhancing features including lifting strakes, trim tabs and variable drive angle were tested. These additions were found to have a profound effect upon the conditions at the inception of porpoising.

Established planing hull analysis methods were augmented with techniques developed during the course of the study to provide a basis from which to design and outfit high-speed, heavily laden planing hulls with respect to porpoising stability.

Keywords

1. Porpoising: Coupled oscillations in pitch and heave of constant or divergent magnitude.
2. Planing: Operation in which dynamic lifting forces provide the majority of the required support. A planing craft appears to ride on top of the water.
3. Stability: The ability to operate at a steady state condition, and return to that same condition after a disturbance.
4. V-Hull: A hull with reasonably straight buttock lines and a clearly defined "V-shaped section, measured by the deadrise angle.
5. High-Speed: Operation at speeds such that porpoising may occur.

Nomenclature and Symbols

α= trim tab deflection
b= beam overall
b_{PX}= maximum chine beam
β= deadrise angle
CG= position of center of gravity
LCG= longitudinal position of center of gravity measured forward of transom
VCG= vertical position of center of gravity, measured above keel
Δ= displacement
g= acceleration of gravity= 32.17 ft/sec^2

$$C_\Delta = \frac{\Delta}{\rho g b^3} = \text{ load coefficient}$$

$$C_\delta = \frac{\Delta - \text{Tab Lift}}{\rho g b^3} = \text{ load coefficient adjusted for trim tab lift}$$

$$C_{Lo} = \frac{\Delta}{\frac{1}{2}\rho V^2 b^2} = \text{ lift coefficient for a flat planing surface}$$

$$C_{L\beta} = \frac{\Delta}{\frac{1}{2}\rho V^2 b^2} = \text{ lift coefficient for a deadrise planing surface}$$

$$\frac{dC_L}{d\alpha} = \text{Lift Curve Slope}$$

HSAC MKII= 40' High-Speed Assualt Craft, MKII
LOA= length overall
LBP= length between perpendiculars
L_C= chine wetted length
L_K= keel wetted length

$$\lambda = \frac{L_K - L_C}{2b} = \text{ mean wetted length to beam ratio}$$

$$L_{TAB} = \frac{1}{2}\alpha \frac{dC_L}{d\alpha}\rho V^2 A = \text{Trim Tab Lift}$$

$$C_V = \frac{V}{\sqrt{gb}} = \text{ speed coefficient}$$

λ_{DH}= scale ratio for Day & Haag data
NAHL= Naval Academy Hydromechanics Laboratory
NSWC= Naval Surface Warfare Center

PCC= 42', waterjet powered Patrol Craft, Coastal
PVC= Polyvinyl Chloride
ρ= water density
V= speed of craft

Background

Planing craft are high-speed marine vehicles that derive most of their support from hydrodynamic pressures acting on their relatively flat, wide bottom surfaces. While the concept of planing was recognized in the late nineteenth century, the first practical application of the concept can be traced to the development of seaplane hulls during the beginning of the twentieth century. As power plants became light and powerful enough to propel a small to medium size boat past its "hump speed," defined by the generated wave patterns, into the planing speed regime, a whole new facet of marine transportation began. While the planing hull introduced the ability to operate at high speeds across the surface of the water, it can easily fall victim to dynamic instabilities, which have manifested themselves in both vertical and transverse responses. In mild cases, these instabilities can be a mere annoyance, but in the most extreme cases, they have led to catastrophic structural failure, to capsizing and to serious personal injury. One of the most common instabilities, known as "porpoising," is a vertical plane, coupled oscillation in pitch and heave which occurs in calm water, and can be divergent in magnitude. Porpoising inception and the craft parameters that influence it are the subjects of the research described in this report.

Planing craft have taken various forms, dependent upon the design speed and intended operational profile. The hull forms addressed in this paper are those designed for high-speed operation under moderate to heavy loading conditions. The typical bottom design for such craft include sharp corners at the chines and transom that ensure distinct water flow separation to minimize hull side flow attachment and to maximize dynamic lift. Without these sharp corners, the flow paths would become unpredictable, planing resistance would increase, and dynamic lift and stability would suffer. Hulls belonging to this family are known as "hard chine planing hulls."

The simplest of these planing hull forms are "prismatic" in form, meaning that from a point around amidships continuing aft, the planing surface has a constant deadrise and chine beam; i.e., the afterbody is a prism from a hydrodynamic standpoint. "Deadrise" is the transverse slope of the bottom of the boat, measured in degrees. Thus, a boat with zero degrees of deadrise would have a totally flat bottom. The angle of deadrise of a planing surface has an effect on the calm water stability and performance of the craft. The deadrise angles analyzed in this study range from 15 to 25 degrees, which span the majority of high-speed offshore "V-hulled" boats. Hulls with more than approximately 22 degrees are referred to as "deep-V" forms and are renowned for their ability to perform at high speeds in rough water at the expense of increased resistance. A "non-prismatic" hullform can have one or more deviations from the simple prismatic shape including variable deadrise along the hull length, typically decreasing toward the stern of the boat and tapering of the chine beam toward the after end of the hull. Reverse chines, flat strips at the outboard edge of the planing bottom, and running strakes are located longitudinally along the planing surface to help improve lift on heavily laden hulls. Both reverse chines and running strakes can extend forward and serve as spray rails that deflect the spray away from the hull, keeping passengers and cargo drier.

Other features found on high-speed hulls are keel pads, transverse steps, transom notches and trim tabs. A keel pad appears as an extra piece of hull attached to the bottom of the hull along the keel in the after portion of the boat, creating, in effect, a longitudinal step. The intent of any step is to reduce the wetted surface area and, therefore, the viscous resistance from water flow. The transom notch increases the distance between the trailing edge of the planing surface and the stern drives. This allows the drives to be mounted vertically higher than normal. At slow speeds the wake rises up far enough to immerse the propellers, giving plenty of thrust and resistance to cavitation. At higher speeds, the wake flattens out, bringing up to half of the propeller out of the water, reducing the viscous drag from the drive and propeller, allowing higher top speeds. Hence, the transom notch serves as an automatic "jack plate" which outboard racers and bass type fishing boats have long used to vary their propeller height. Figure 1 displays the properties of a typical high-performance "V-hull".

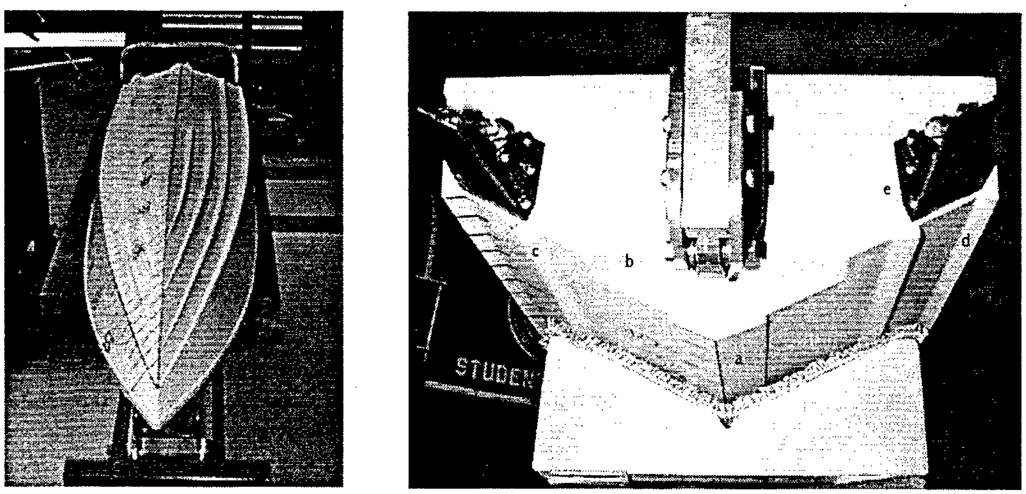


Figure 1 – Views of modern planing hullform, with trim tabs
a, keel pad; b, transom notch; c, running strake; d, reverse chine; e, trim tab

Propulsors for high-speed "V-hulls" come in various forms, but most are both steerable and trimmable. Adjusting the trim of these stern drives vectors the propulsive force in the vertical plane, affecting the running trim angle of the boat. Also, adjusting the drives' trim varies the depth at which the propeller(s) are operating. Propellers set up to run partially submerged are known as "surface piercing drives," and adjusting the trim angle of the drives varies the immersion of the propellers, allowing the required torque to be adjusted to match the torque characteristics of the engine(s). Finally, trim tabs are planes mounted on the transom near the outboard sides and are normally adjustable underway through hydraulic pistons or linear screw drives. These trim tabs, also commonly referred to as transom flaps can be a sizable percentage of the wetted hull area at high speeds and provide a lifting force and a bow down pitching moment which are used primarily to compensate for both transverse and longitudinal variations in loading condition. As will also be seen, the lift that these tabs provide completely alters the planing dynamics and can be used to stabilize a boat that would otherwise porpoise.

The focus of this study is to define the limits of the vertical dynamic stability of hard-chine "V-hulls" accurately with regard to porpoising, which can be best described as a periodic oscillation in both pitch and heave of constant or increasing amplitude. Pitch angle is the dynamic equivalent of static (longitudinal) trim angle and, for all cases in this report, it is referenced to the keel of the planing surface in the afterbody of the hull. Since the boat rises dynamically on its lines and trims aft, it is this afterbody which produces the dynamic lift, is responsible for the residual hydrostatic force, and, therefore, determines the calm water running characteristics of the hull. Since the afterbody shape of most "V-hulls" is semi-prismatic, the underwater shape is simple and predictable which simplifies the analysis, enabling a valid approximation to be made.

Previous studies conducted by Perring (1933), Day & Haag (1952), Clement and Blount (1962), Savitsky (1964 & 1976), Fridsma (1969), Martin (1978), and others using both models in a towing tank and full scale craft, have established that the inception of porpoising is a function of speed, loading, trim angle, longitudinal center of gravity and hull deadrise angle. The report by Day & Haag is clearly the most systematic with regard to porpoising, and was the only study in which systematic experiments were conducted specifically with the intention of discovering the porpoising limits. The others reported porpoising when it interfered with the results of other tests. Perring and Martin derived theoretical predictive methods that relied on high-order transfer function stability derivatives. These methods are commonly used to analyze electrical and mechanical systems and have great potential for hydrodynamic analysis, as long as the nature of all the forces and moments acting upon the vessel can be accurately predicted. These methods lost accuracy as speed increased. Since porpoising becomes more than just an annoyance in the high speed range, leading to loss of control, payload damage and structural hull damage, it is apparent that a reliable predictive method which would guide designers, outfitters and operators of these exciting craft would be of value to the quest for safety and efficiency of high speed marine transportation.

Preliminary Analysis

As Naval Architecture is very often an empirical science, it was apparent that the best way to begin a study of the causes of porpoising would be the analysis of model testing results. Many reports from planing boat tests have made reference to porpoising as it affected calm water resistance testing, but only one systematic model testing program has been conducted to date with the specific intention of charting porpoising using hard chined planing boats. Day & Haag, in their 1952 Webb Thesis, made use of the Webb Institute of Naval Architecture's towing tank to conduct their experiments. Their "boats" were three tiny prismatic forms constructed from basswood, and had beams ranging from 3.7 to 3.89 inches. When hard chine boats plane on calm water, only the aft half of the boat generally is in contact with the water, and therefore the bow design is of little consequence unless a study of the actual porpoising amplitudes were attempted. Day & Haag were challenged by the light weight of these models, and also by the fact that no lightweight electronic trim sensor existed in 1952. Therefore, they opted to install a scribe arm vertically from the boats, the motions of which caused the scribe to etch an elliptical pattern on a sheet of smoked glass above the model. The amplitude of the coupled pitch and heave motions due to porpoising was proportional to the size and shape of the ellipse inscribed.

There was little doubt, given the painstaking setup performed by Day & Haag and the credentials of their advisor, Professor B.V. Korvin-Kroukovsky, that the data from the tests were accurate. The chief reason for conducting a new set of porpoising tests was to ensure that the inception of porpoising was a scalable quality of a planing hull, as the method of Froude Scaling used re-creates the wave train and the pressure field generated by the boat, but not the viscous effects of the fluid flow. If porpoising were caused by a viscous phenomenon, there would be no hope of extrapolating the results of a model test to full scale. Prior to conducting the tests, tidbits of porpoising data were gleaned from the calm water resistance tests conducted by Clement & Blount (1963), and Fridsma (1969). Both of these experimental programs were performed using much larger models than Day & Haag. Clement & Blount produced a plot of the porpoising boundary, in terms of the placement of the longitudinal center of gravity and Volumetric Froude Number. While quite reliable when used with the Series 62 non-prismatic planing hulls, discrepancies between the scaled LCG values for other craft were found. For the present study, all relevant data were converted to a consistent set of parameters, input into a spreadsheet, and plotted many different ways in an attempt to determine what relationships existed. It was found that the non-dimensional position of the center of gravity, G, was not an especially good predictor of either trim angle or the inception of porpoising. This non-dimensional, longitudinal position of G is found by dividing LCG (distance of G forward of the transom) by the boat beam. In addition, LCG does not account for any variation in propulsive angle or for the effect of trim tabs, both of which have been proven to have an effect on the porpoising inception of modern full scale boats.

Day & Haag utilized many of the principles which had been established during the testing of seaplane floats and confirmed for a planing boat, that the inception of porpoising was a function of trim angle, load coefficient, speed coefficient, and deadrise. Because these parameters definitely showed the best correlation, it was decided that the attempt to establish a predictive method for porpoising should begin by studying those parameters and their individual effects upon inception.

By using a spreadsheet on a personal computer to analyze the data, the available calculating power is beyond even the most far-fetched hopes of Day & Haag in 1952. The intent of the analysis was to find either a critical value of some combination of the parameters, or a function that could be used to predict the values of the parameters when the inception of porpoising was reached. Upon analyzing the critical porpoising trim angles from the prismatic testing done for this study, it was found that when they were plotted against the $\sqrt{(C_L/2)}$ term, as Day & Haag had done, the curves that were generated followed natural exponent curves, each deadrise having a different constant and exponent. Curves for each deadrise were faired, then a regression was performed to yield:

$$\tau_{crit} = 0.1197 * \beta^{0.7651} * \exp\left(15.7132 * \sqrt{\frac{C_L}{2}} * \beta^{-0.2629}\right) \text{degrees} \tag{1}$$

A simple relationship between C_L, C_Δ, and C_V reads:

$$\sqrt{\frac{C_L}{2}} = \frac{\sqrt{C_\Delta}}{C_V} \tag{2}$$

The range of applicability for Equation (1) is at least as wide as the parameters tested for these experiments. C_Δ varied between 0.392 and 0.525, C_V between 2 and 4.7, and β between 15 and 20 degrees. Equation (1) may provide logical predictions outside this range, but has not been validated. Day & Haag showed that C_Δ values as high as .720 fell on the same $\sqrt{(C_L/2)}$ curve. Equation (1) obviously becomes invalid for $\beta = 0$ degrees deadrise. There are hulls in service which operate at lighter load coefficients than those addressed, but these craft present a difficult analysis problem. The chines of lightly loaded "V-hulled" craft, will become dry when the boat comes to a fully planing condition, and the water flow breaks directly off the transom vice the chine. Unless the actual wetted beam were used, the lifting coefficients would not produce the proper planing force, along with a host of other problems. For the purposes of this paper and predictive methods, lightly loaded hulls are neglected, and the focus is maintained on medium to heavily laden craft (typical of modern combatant boats) for which the water flow reaches the chine.

Discussion

For a deadrise planing surface operating at high speed, the water flow begins at the intersection of the keel and the calm water surface. Spray is developed which travels aft and outboard from the keel. The flow of solid water follows essentially a straight line from the keel to a point at the chine, further aft on the hull, where the flow separates from the hull. Just aft of this line is the stagnation line, the line at which the highest local pressures exist. When the local pressures are integrated over the bottom, the resultant center of dynamic pressure falls roughly around the ¼ chord point of the wetted surface. Remembering that the leading edge of the wetted length is shaped as a "V" when viewed from overhead, the angle at which the stagnation line is swept back is a function of the shape of the leading edge of the wetted surface.

An investigation into the cause of porpoising must analyze the response of the location of the center of pressure on the bottom of the boat as a function of a minute change in trim angle, for which an equation can be written. Essentially, if the first derivative of this function could be found with respect to trim angle, the magnitude of the moment produced could be determined for the minute trim change. The case in which the running trim angle is low yields a stable system because as the boat trims, the keel wetted length changes, but the wetted chine length does not change very much. Therefore, the position of the center of pressure changes only minimally. For the case in which the initial running trim angle is high, a trim change produces large changes in both the keel and chine wetted lengths, yielding a larger movement of the center of pressure. At some critical trim angle, the moment produced by the response of the movement of the center of pressure becomes greater than the moment that initially caused the disturbance. The disturbance can be as great as the boat impacting a wave, or as minute as the basic variations in turbulent fluid flow.

Figure 2 shows the shape of the wetted area of a planing hull, and also graphically represents the difference between a porpoising condition and a stable condition. When a single, instantaneous disturbance is applied, the virtual center of forces, similar in concept to the center of gravity, but accounting for all internal masses and external forces, moves slightly. The virtual center of forces is an imaginary point about which trimming moments due to propulsive forces (thrust and vertical force), appendage forces (lift and drag), and hull friction forces are summed and the resultant is assumed to act. The response of the center of pressure for the unstable case is seen to move ahead of the virtual center of forces, causing an overcompensation in trim. For simplicity's sake, the center of forces is taken to remain constant after the disturbance, when actually it could move slightly as a function of trim angle. For a stable case, a disturbance results in movement of the center of pressure just sufficient to reach a new state of equilibrium. The disturbance may cause a few oscillations, but the boat quickly settles back to its original attitude.

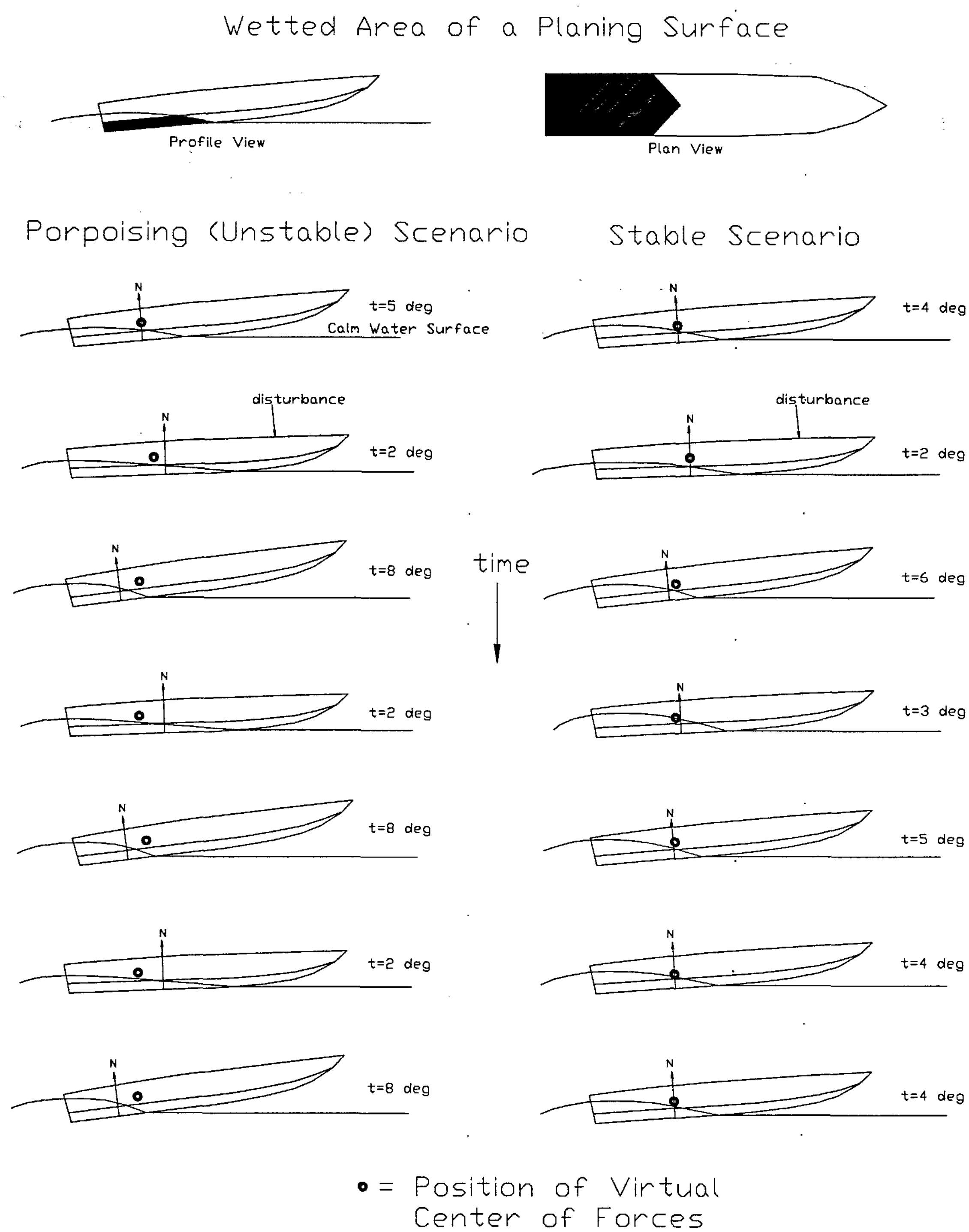


Figure 2 – Wetted Area of a Planing Hull,
Graphical Representation of Porpoising and Stable Conditions

To date, the porpoising of planing hulls has been analyzed empirically from an external point of view. A study into the actual cause of porpoising is therefore warranted. Remembering that the lift on a planing surface is comprised of two parts, both hydrodynamic and hydrostatic, their interaction is the logical starting point for such an analysis. The long-standing equations used to predict the lift developed by deadrise planing surfaces are theoretically based, with empirical coefficients from test data.

$$C_{L_o} = \tau^{1.1}\left(0.0120*\lambda^{1/2} + \frac{0.0055*\lambda^{5/2}}{C_V^{\ 2}}\right) \tag{3}$$

Equation (3), originally developed by Sottorf in 1933, then modified by Savitsky in 1954, predicts the lift coefficient based upon λ, the mean non-dimensional wetted length and the speed coefficient of the planing surface, not to be confused with the symbol λ when used to refer to geometric scale ratio. The two terms inside parentheses represent the two components of lift, the first being hydrodynamic and the second hydrostatic. Logically, as wetted length increases, the lift coefficient increases at a lesser rate due to the decreased aspect ratio. The hydrostatic lift term is based on the submerged volume and decreases as speed increases. Note that unlike modern airfoil theory, which uses the surface area to non-dimensionalize the lifting force, planing hull analysis utilizes the beam squared as the non-dimensionalizing parameter, as shown by:

$$C_{Lo} = \frac{L_o}{\frac{1}{2}*\rho*V^2*b^2} \tag{4}$$

C_{Lo} is the lift coefficient generated by a flat plate, or a hull with zero deadrise angle. To predict the reduction in lift experienced by a deadrise surface relative to a flat surface, the following equation has been used, where β is in degrees. $C_{L\beta}$ is also called the required lift coefficient.

$$C_{L\beta} = C_{Lo} - 0.0065*\beta*C_{Lo}^{\ 0.6} \qquad \beta \geq 0 \tag{5}$$

The analysis was carried forward from the development of the critical porpoising trim angle to determine the individual effects of the hydrodynamic and hydrostatic components of lift. A computer program was developed which would utilize Equation (1) to predict the critical porpoising trim angle at increments across the speed range for a given deadrise and loading for an imaginary deadrise planing surface. The program then determined the theoretical $C_{L\beta}$ and C_{Lo} based on those parameters. An iterative solution method was used which would determine C_{Lo} since it appears in Equation (5) twice. Equation (3) was then implemented, and a similar iterative solution method was set up to determine λ. The mean wetted length now known, the individual components could be determined, and their individual contribution to lift analyzed.

It was found that when the trim angle was constrained across the speed range to the critical porpoising angle, the percentage of lift generated hydrodynamically increased with increasing speed, while the remainder, the hydrostatic lift, decreased as speed increased. This analysis proved fruitful when it was found that the relative percentages of these components remained virtually constant over various combinations of deadrise and displacement from $C_V = 2.5$ to $C_V = 5$. The maximum error between different cases in this range was two percent while C_Δ was varied from 0.25 to 0.57 and deadrise from 15 to 25 degrees. On the basis of this observation, a curve was generated which appears in Figure 3. It is important to note that as either displacement or deadrise changes, the critical trim angle changes noticeably. However, at the critical angle, the percentage of contribution of each component remained near the curve. Remembering that Equation (1) was developed empirically, as were the previously developed planing equations, a two percent error could be expected. When trim angle was varied from the critical trim angle, a relatively large change in the lift component ratios was observed. A trim angle increase tends to invoke more hydrodynamic support as less hull length is wetted and angle of attack increases. Conversely a trim decrease causes more lift to be provided by hydrostatic means as wetted length increases and angle of attack decreases.

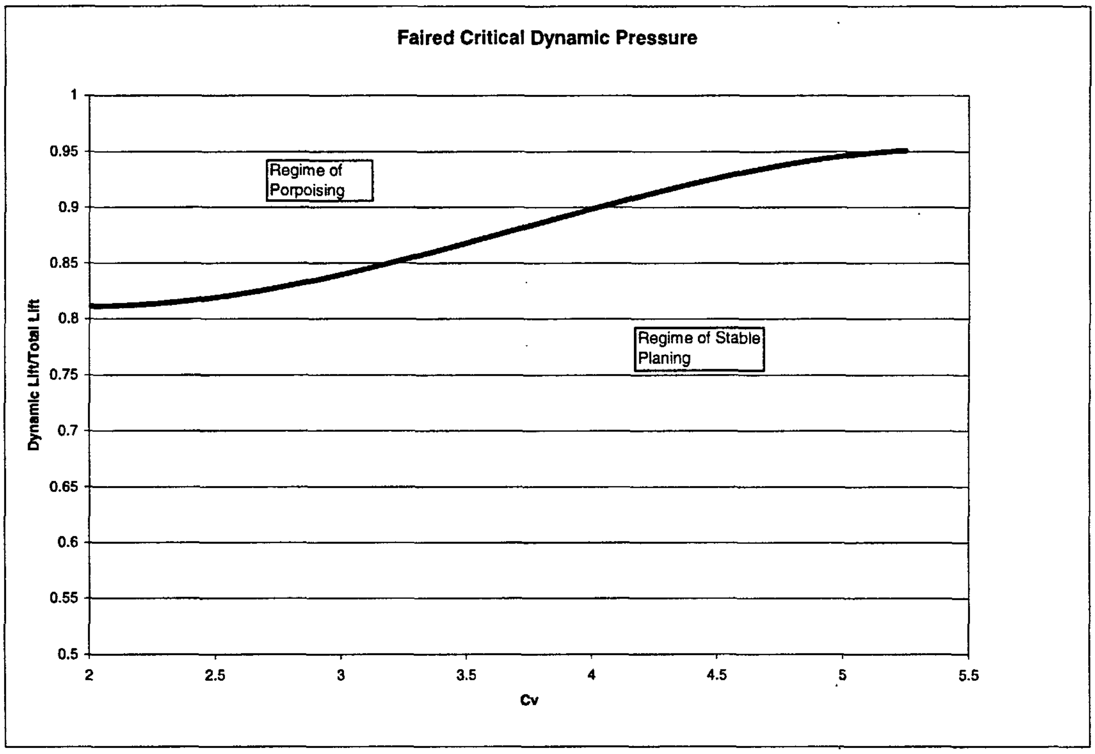


Figure 3 – Percentage of Lift Dynamically Generated at Porpoising Inception

The above mechanism suggests that there exists some natural limit defining how much dynamic lift a hull will generate at a given speed. Once this limit is exceeded, the trim angle will fall, resulting in more support being provided hydrostatically. Porpoising results when a significant overshoot in this lift transfer occurs and the oscillation continues. Assume, for simplicity, that a prismatic planing hull at speed has the shape of a right triangle with the still water as the hypotenuse and the transom and bottom as the mutually perpendicular sides. The hydrodynamic lift component is assumed to act at three-quarters of the mean wetted length forward of the transom, or the one-quarter chord point, a practice derived from wing lifting theory. The hydrostatic support for a triangular prism is based solely on the submerged geometry, and is one-third the mean wetted length forward of the transom.

Testing Part I

The purpose of the first series of towing tank experiments was to reproduce the tests performed by Day & Haag in 1952, and to ensure that the results were applicable to model boats of a larger scale. The U.S. Naval Academy's Prismatic Planing Series hulls were used. The series consisted of three models. The overall beam was 18 inches, and the chine beam was 17.5 inches for each. Each model had a different deadrise angle, the shallowest being 15 degrees, the middle 20 degrees and the deepest was 25 degrees. Each boat had the same 5 inch high hullside, and an identical chine plan. The overall depth of the 25 degree model was over 2 inches greater than the 15 degree deadrise model giving a much fuller appearance. Figure 4 shows all three models together from astern.

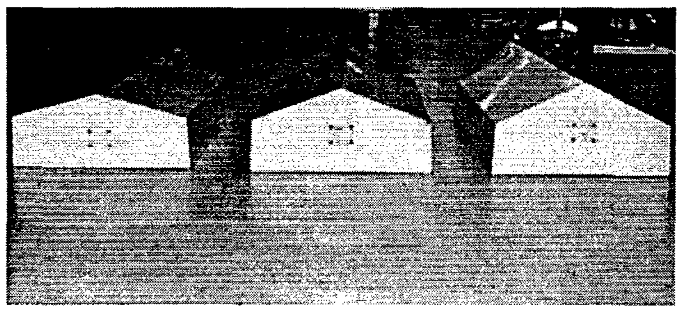
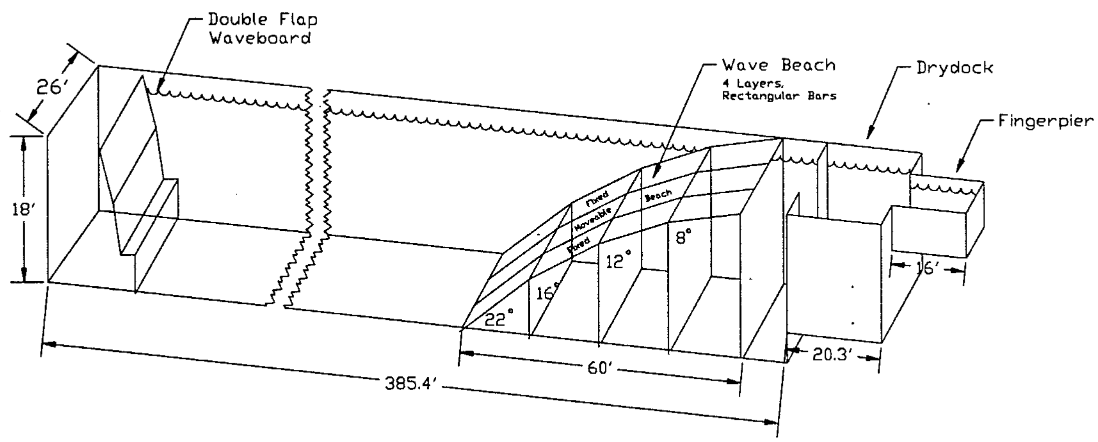


Figure 4 – NAHL Prismatic Planing Series, β = 15, 20 and 25 degrees

The models were refinished specifically for this testing program. Each was painstakingly epoxy-filled, sanded and painted standard model testing yellow by Mr. William Beaver of the U.S. Naval Academy's Technical Support Division. The primary purpose for this work was to ensure that each model had a fair surface, and that all corners were sharp and free of imperfections which might hinder flow separation, causing inaccurate results at some speeds.

The testing was conducted in the U.S. Naval Academy Hydromechanics Laboratory, shown in Figure 5. The 380' tank offers one of the longest testing lengths for high-speed work available at an undergraduate institution. The tank cross section measures 26' wide and 16' deep. The resulting cross sectional area, A_{tank} must be large enough relative to the maximum sectional area of the model, A_{model}, such that the model hydrodynamics are not influenced by the proximity of solid boundaries. For all model testing conducted for this project, ${}^{A_{model}}/_{A_{tank}} < {}^{1}/_{1300}$ which is well below the empirically established criterion of ${}^{1}/_{200}$ considered adequate to prevent blockage and pressure effects from the tank walls. The tank has a specially designed "wave beach" at the northern end, which dissipates waves created by the double flap MTS wavemaker located at the southern end. Since porpoising is a calm-water phenomena, the wavemaker was not used, but the wave beach and the swimming pool type lane marker, which runs the length



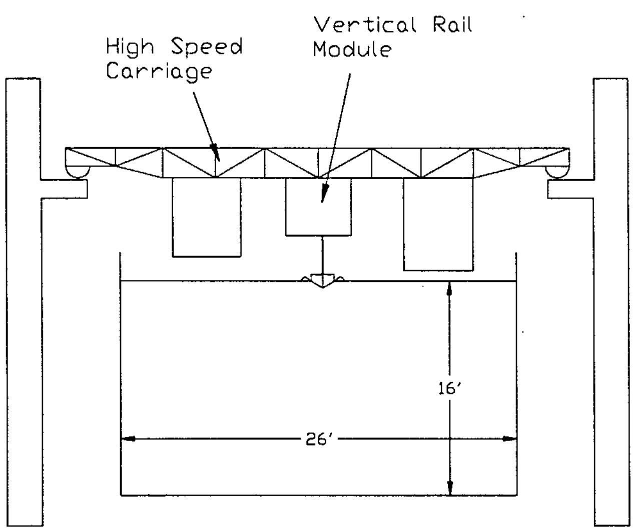


Figure 5 – NAHL 380' High-Speed Towing Tank

of the tank on the right side, were critical to the experiments in that they absorbed the boat's wake after each run. For the heavier displacement runs, approximately 15 minutes were required for the wave disturbance to die down, even with the lane marker and wave beach in place. The normal testing arrangement consists of a high-speed and a low-speed module connected together in the form of a tractor-trailer configuration. This arrangement has a top speed of 25 feet per second and weighs approximately 40,000 lb. The high-speed carriage can run at speeds up to 32 feet per second and weighs approximately 8000 lb. It is supported by four roller-chain bearings riding on 3 inch diameter, case hardened steel rails that run the entire length of the tank. These cylindrical rails provide a very smooth ride, necessary for conducting precise research.

The propulsive force is provided by two AC motors located at the southern end of the tank behind the wavemaker assembly. These motors are rated at 400 hp each, with a 1600 hp total peak rating. They are geared to a continuous cable drive that is always attached to the high-speed carriage. The carriage speed is controlled from a room located near the northern end. Because of the danger and potential for serious injury to anyone riding the carriage at near maximum speed, special attention has been given to the carriage stopping system. When the carriage operator sets the desired speed, he also dials in a stopping point, in feet from the end of the tank. The optimum points have been determined by the lab staff empirically, with the goal being to gain the longest possible run time and still stop safely. The normal stopping mode decelerates the carriage at approximately 0.25g. Should the operator miscalculate the stopping point, or the normal system fail, a separate emergency stopping circuit is provided which arrests the carriage at approximately 1g. In the extremely unlikely case that the emergency stopping circuit should fail, an arresting wire has been provided which physically arrests the carriage. The last line of defense consists of a pair of hydraulic damper pistons, which, if hit, would provide a deceleration just shy of impacting a brick wall. Figure 6 shows the high-speed carriage, with a model attached beneath the vertical rail module.

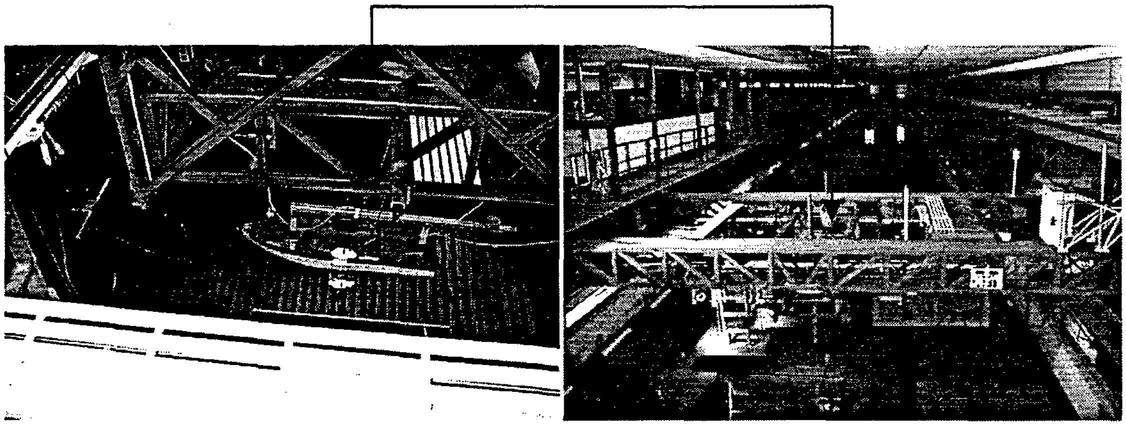


Figure 6 – Vertical Rail Module with model (left) and High-Speed Towing Carriage

The small prismatic models used by Day & Haag were tested in the 94' x 10' x 5' towing tank at Webb Institute. Their work represents the current industry benchmark for predicting the inception of porpoising of planing boats. Day & Haag towed their models using two light cables. The goal for such a setup was to eliminate all unwanted damping forces on the light models, which might have prevented porpoising inception. Their towing point was determined by using Equation (6), which determines the towing height above the baseline, H_V as a function of H_C, the height of the chines above the baseline, and b_{PX}, the chine beam. The linear scale ratio, λ_{DH} was introduced into Day & Haag's equation to account for the size difference between the two sets of models.

$$H_V = .4 * H_C + 2.10 * \lambda_{DH} * b_{PX} \qquad (6)$$

This towing height was empirically selected with the intention of keeping the towing lines above the spray coming from the boat. Day & Haag pointed out that since planing boats could be propelled by any means of propulsion, any propulsion point could be assumed. This is reasonable for a general case. The second portion of this testing program investigates the effects of geometrically scaled application of the towing force. The towing rig pictured in Figures 6 and 7 was designed to be geometrically similar to Day & Haag's.

For a planing hull, the beam, b, is used as the characteristic length when making nearly all dimensionless calculations required for scaling. This is logical because planing is a dynamic condition, and usually a large fraction of the hull is out of the water at speed. Therefore, the only parameter that does not vary with speed is beam, at least at moderate to heavy loading. This technique is used not only for linear measurements, but also for determination of lifting, speed, and displacement nondimensional coefficients. The scale ratio between Day & Haag's models and those used for this test was λ_{DH}=4.73, based on beams. The longitudinal position of the towing point was scaled linearly as well and was set to 27.1 inches forward of the transom for the present NAHL tests.

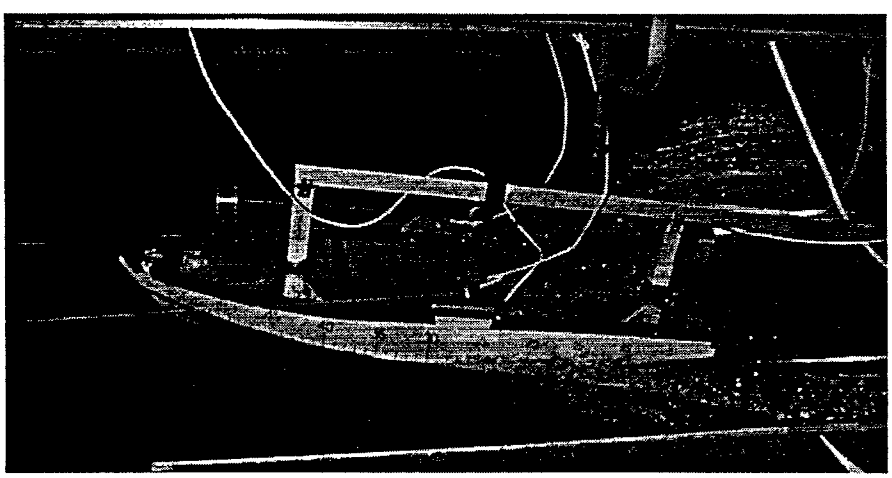


Figure 7 – 20 Degree Deadrise Model

The towing rig was completed by clamping a sturdy vertical steel post to the forward end of the high-speed carriage. A 500lb capacity force block, used to measure the resistance of the boat, was mounted at the bottom of the vertical post. Given that the experimenter knew beforehand the approximate range of resistance values, using the 500lb unit to measure force magnitudes of 15 to 30lb does not seem like a prudent choice, because the resolution of the 500lb unit is on the order of 1 lb. The next smaller unit available had a maximum rating of 100 lb., which would have worked very well for measuring the steady state resistance force, and would have easily tolerated the forces due to the normal carriage acceleration rate of 8.3 ft/sec^2. The 100lb block was not used for fear of damaging it should an accident occur. The towing arrangement was such that the potential existed for the model to broach or to submarine, either of which could produce very large forces. Calibration curves for all data acquisition modules appear in Appendix B.

A spreader bar consisting of aluminum channel was bolted to the bottom of the force block, visible at the extreme left of Figure 7. The towing cables had thimbles installed at either end, and both cables were within $^1/_{32}$" of being identical in length. The towing length was arbitrarily set at 84" to place the model beneath the vertical rail module of the high-speed carriage, as the towing length in fact had little significance on the inception of porpoising. Day & Haag did not give any justification for setting their towing cable length. More important was to ensure that the cables were as near to horizontal as possible, that they were the same length, and that they were parallel. The steel post was adjusted to bring the towing point to 8 ½" above the water's surface, which brought the cables parallel to the water when the model was operating at planing speed. Two $^1/_8$" aluminum plates were bolted through the hull sides, and braced by a horizontal aluminum strips which rode on the gunwale of the boat, helping to distribute the potentially large towing forces. The hullsides of this model were never intended to be a towing point. This setup proved effective, and caused no problems. Figures 6 and 7 show the cable attachment to the force block and to the model for the Day & Haag validation test.

A major requirement for the testing was the ability to make significant changes to the longitudinal position of the center of gravity quickly and accurately. This was accomplished by fabricating two vertical posts from 2" x 2" hollow rectangular aluminum tubing. Large bases were constructed to help distribute the load, and each post was attached "truss style" to its base. A hole was drilled near the top of each post for the 50" weight-carrying rod made of ½" threaded rod to pass through. The rod was 15" above and parallel to the keel. Because of the mechanical data measurement rig used by Day & Haag, a very large radius of gyration, k_{yy}, was produced. Although the argument had already been made (that longitudinal moment of inertia would not have any significant effect upon the inception of porpoising), an attempt to scale the radius of gyration was made on the intuitive expectation that porpoising frequency would be affected by longitudinal moment of inertia. The resulting model configuration can be seen in Figure 7. The longitudinal 2" x 2" tube bolted to the top of the weight posts allowed for not only the vertical center of gravity to be scaled properly, but also for

weights to be placed aft of the transom. The longitudinal position of CG could not be driven far enough aft while maintaining the necessary radius of gyration without moving the rear weight aft of the transom.

Once set up, the light load condition displayed sufficient transverse stability to remain upright during the rather violent decelerations. The heavier loading had only marginal transverse stability, and would have capsized easily. Therefore, VCG was reduced slightly below its scale value for that test condition. Since the model was expected to become partially submerged during stopping at heavier loading conditions, a ¼" sheet of Plexiglas was cut to serve as a deck for the model. Holes for the vertical weight posts and towing brackets were sealed with vinyl tape. During stopping, the model's wake would consistently wash up on the deck, while at the same time, the model would swing back on its stopping mechanism, forcing the stern even further under the water. The model would have been swamped after every run without the deck.

While pulling the model at speeds of up to 32.0 ft/sec presented no challenge, special attention had to be paid to designing an arresting mechanism that would safely absorb the stopping forces. Day & Haag developed a stopping mechanism that lifted progressively more chain as the model traveled past the desired end of the test run. A similar mechanism was not practical for the NAHL carriage, so an arresting mechanism was designed using four pieces of nylon line, chosen for its relative elasticity. The criteria for designing such a system were that it must not interfere with the porpoising motions of the boat, nor apply any significant extra weight to the model while running. The two towing points, as well as the rear post of the weight-carrying bar were used as attachment points. The end of each line was shackled to selected points on the carriage. Shackles were used so that the model could be removed from the rig easily, and yet be identical for each day's testing. The lengths of the lines were adjusted so that they all came under tension evenly when the boat surged forward. This rig provided controlled stops, and even kept the model safe during an unexpected 1g stop.

The model selected for towing in this manner was the 20 degree deadrise prismatic hull because it was the only available model that matched one of Day & Haag's models in terms of deadrise angle. The NAHL model was run at Δ=76.06 lb., and Δ=101.2 lb. The speeds for each run were determined by Froude Scaling Day & Haag's test conditions. The original intention was to replicate Day & Haag's tests exactly, but only after the whole initial series of tests were complete was it realized that the actual chine beam of the prismatic model series was only 17.5", and not the 18.0" originally assumed. Although prismatic in form, the hullsides of the NAHL model have a slight flare, which reduces the chine beam by ½" from the maximum beam at the gunwhale. Since load coefficient is a function of the chine beam of the boat cubed, the ½" did make a substantial difference in the results. In retrospect, however, this mistake was fortunate because, after the appropriate corrections were made, the results followed the Day & Haag trend more closely.

The results of the initial porpoising tests using the cable-towing rig are displayed in Figure 8. Plotted with the data points are the predictive curves from Equation (1) for the corresponding C_Δ and β values.

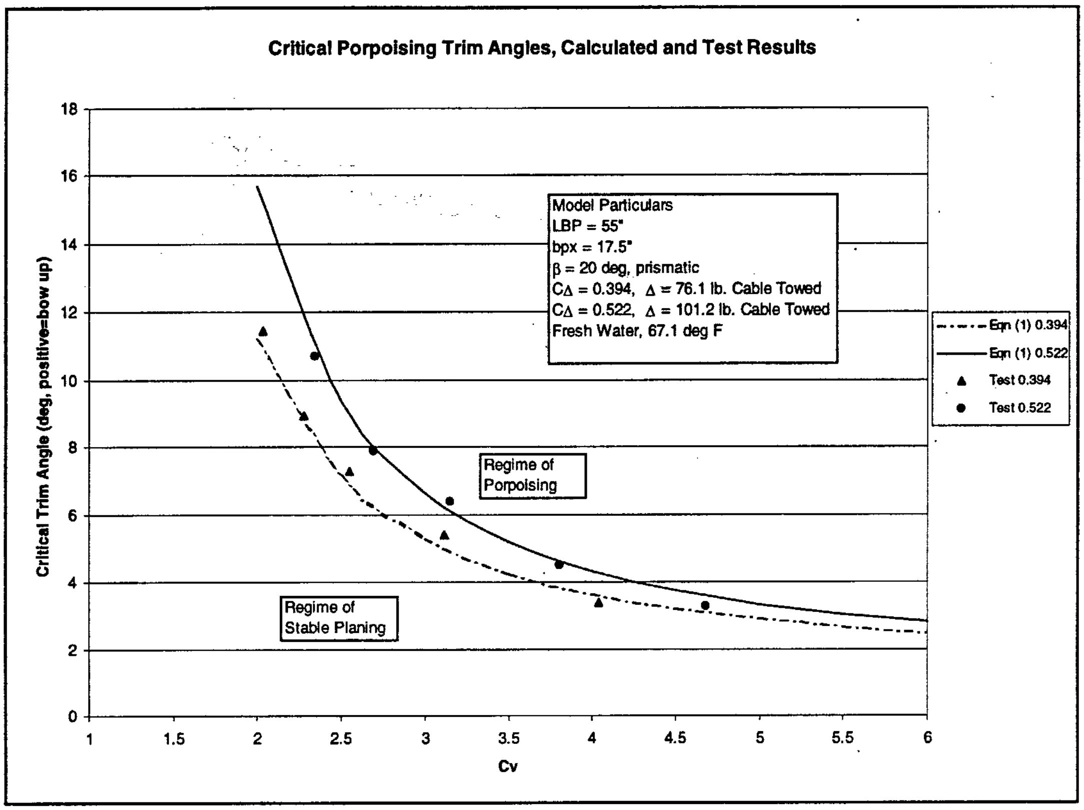


Figure 8 – Results of Cable Towed Experiments vs. Predictions.

Given what has been established so far, it is possible to determine the critical running trim angle of a boat below which it must stay in order to avoid the inception of the porpoising. From a purely operational standpoint, the experienced operator might be able to make underway adjustments to the control surfaces and outdrives to keep the boat trimmed below the critical trim angle by feel, without working equations or looking at an inclinometer. What the operator cannot do underway, however, is what the designers and outfitters should do in the early stages of design and construction. The ability to ensure that the trim tab size, range of deflection and range of motion of the drive unit are sufficient to stabilize the boat across the speed envelope is the logical application of a predictive method.

Testing Part II

Following the reproduction of Day & Haag's cable towed experiments, the next challenge was to implement a prototype outdrive towing rig, which would apply thrust to the model in a manner more similar to a full scale craft. This effort was considered necessary to quantify the effect of thrust vector location and direction on porpoising inception. The design for the new towing setup evolved over a period of several months. Given that the program's intent was the search for the porpoising inception boundaries, the following criteria were established for the design of a new towing rig:

1. The rig must allow freedom in both pitch and heave with minimal damping.
2. The rig must not interfere with the inception of porpoising.
3. The location of thrust application should simulate typical stern and surface drives.
4. The angle of the applied thrust must be variable, while still satisfying #1.
5. The rig must be stiff to minimize deflections due to loading, which would skew the angle of applied force.
6. The rig must be easily transferable between models, and installation must not cause irreparable damage to the models.

A ½" diameter hardened steel rod, sliding though a precision linear ball bearing block, mounted to a transversely oriented hinge mechanism, was selected for the towing rig because it satisfied all of the above requirements. During initial testing, the pillow block and rod were loaded in the normal direction with a 20lb weight, with the rod suspended between two platforms, causing the worst possible deflection of the rod. It was determined that the static friction could be overcome by applying 0.8 ounces of force, yielding a coefficient of static friction of 0.0025. Version A of the rig saw the ½" rod anchored to the adjustable towing post, and the linear bearing bolted to the hinged plate on the back of the model. This configuration required that the rod be immersed approximately 7" below the surface of the water in order to ensure that the linear bearing would not slide off the bottom of the rod under acceleration to the planing condition, when the stern temporarily sinks very deeply into the water. This setup resulted in several undesirable effects, both due to the immersion of the ½" rod. First, since the rod was less than 3" behind the transom of the model, it was producing a positive pressure field in front of it of unknown magnitude. Second, water flowing up the rod at high speed would impact the bottom of the bearing block, providing an unquantifiable lifting force. Considerable spray was also formed which impacted both the rig and the model transom. It may have been possible to account for this vertical force, except for the fact that the presence of the model operating at varying displacements, trim angles and speeds in front of the rod would change the amount and speed of the water flowing up the rod. These effects would both result in a lower running trim angle than the model would naturally assume, and would have likely skewed the conditions for the inception of porpoising.

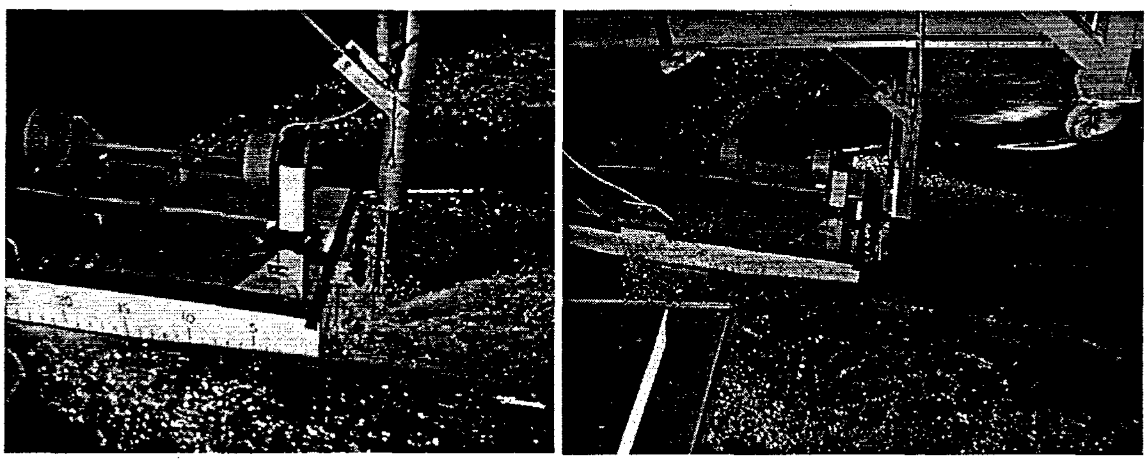


Figure 9 – Towing Rigs A and B with 20 Degree Deadrise Model

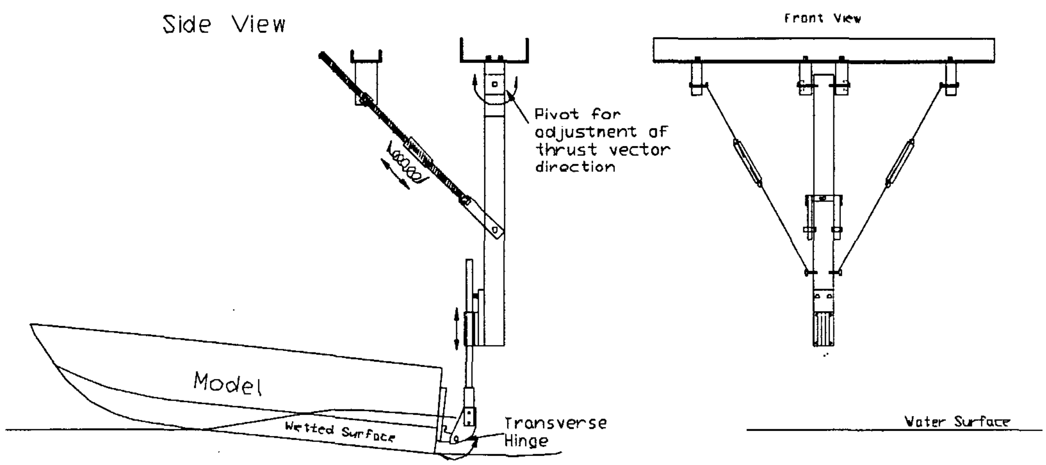


Figure 9A –Towing Rig B

A total of six trial runs were made with the Rig A before the decision was made to dismantle it and use many of the same parts to construct Rig B. The principle of operation remained the same, but the parts were rearranged. A ½" hole was bored longitudinally into a 1" x 1" x 6" aluminum block. The rod was force-fit into it, and secured with set screws. This block was fastened to a plate to which was attached the hinge which would allow pitching freedom.

The vertical height of the transverse hinge axis was the point at which the thrust was taken to act, the values for which are given in Table 1. This hinge point was determined by mounting the towing bracket on each model hull in the lowest possible position without any portion of the rig extending below the expected flow path of the water, eliminating the need to quantify the very complex dynamic forces mentioned above. If any part of the hinge mechanism touched the water, it would be readily

apparent because of the spray and wake patterns produced. The angle of deadrise of the different boats controlled the vertical position of the hinge axis. Rigs A and B appear together in Figure 9. Rig B, on the right clearly results in clean and undisturbed flow from the model transom.

Table 1 – Vertical Location of Thrust Point

Model	Height Above Keel (in)
15 Degree Deadrise	1.5"
20 Degree Deadrise	1.6"
25 Degree Deadrise	2.0"

In addition to the apparatus mounted at the transom, it was necessary to provide yaw restraint since the linear block bearing would not provide any yaw restraint itself. To accomplish this, a fork-like device was constructed by boring parallel ½" holes in a PVC block, and mounting it to the bow of the boat. A 1" rod was fastened to lockable bushings and centered on the vertical rail module in front of the boat, so that the fork mechanism straddled the 1" rod. The spacing of the parallel rods was chosen so as to leave a total of $^{1}/_{10}$" of play laterally to prevent any binding. The yaw restraint kept the boat aligned with the tank during the test runs, and the minimal surface contact between the two hardened steel rods did not appear to apply any significant unwanted damping to the system. On several occasions, either the model's bow or the cap placed on the end of the yaw restraint impacted the 1" vertical rod. Figure 10 shows a model at speed with the bow yaw restraint clearly visible. This occurred mainly on runs with extreme porpoising amplitudes, and did not affect the conditions present at the inception of porpoising. The longitudinal position of the restraining rod was adjustable to suit different models, and different testing conditions.

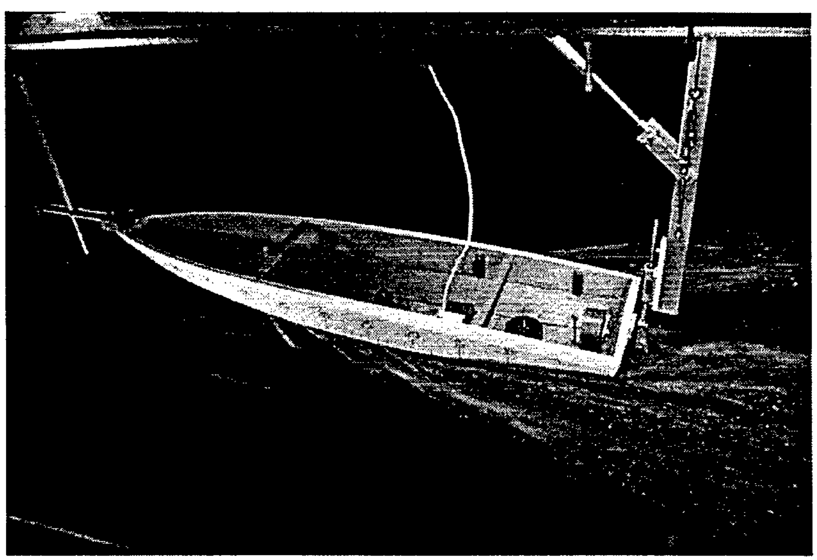


Figure 10 –Towing Rig B, showing yaw restraint and towing bracket.

Testing was begun with the 20-degree deadrise hull for immediate comparison with the testing done with the Day & Haag style cable rig. As expected, the application of the propulsive force at a point low on the transom raised the running trim angle for the same LCG setup. For the NAHL deadrise series, the drive angle was set to a value so as to provide a force perpendicular to the transom, and parallel to the keel, however variations were made on several runs to analyze their effects. Drive trim angle adjustments were accomplished by turning the ½" threaded tie-rod, visible in Figures 9 and 10. The threaded rod was anchored but free to rotate at the vertical post end. The other end was threaded into a tapped aluminum block attached to the vertical rail module of the towing carriage. Adjusting the length of this tie-rod varied the angle of the towing post. The linear block bearing, due to its very low friction was only capable of providing a force perpendicular to the ½" rod. Therefore, when angled, the rod and bearing combination would provide driving force perpendicular to the rod.

Table 2 – Prismatic Hull Porpoising Testing Matrix

Cable Towing Rig				Towing Rig B				
Deadrise	20	20	20	20	25	25	15	15
Δ (lb)	76.1	101	77	102	76.1	101	75.9	101
Speeds	13.90	16.00	15.59	16.00	15.59	16.00	15.59	16.00
Tested	15.56	21.53	17.47	21.56	17.45	21.53	17.47	21.56
ft/sec	17.44	26.05	21.35	26.05	21.35	26.05	21.35	26.05
	21.32	18.41	27.65		27.65		27.65	
	27.65	32.00						

As was done for the first testing series, LCG changes were made to the model for each speed. Pre-test estimates of the LCG values were made by calculating the change in trim moment due to moving the thrust point. The resistance values from the first series of tests were used, and the change in moment was accomplished by moving LCG forward. The LCG and trim angle were recorded at the inception of porpoising for two different loadings for each of three different deadrise models. In general, a porpoising inception point could be determined in three to four runs in the towing tank. The results were compiled and plotted using the method established in the previous section. The required LCG values to achieve stability using Towing Rig B corresponded to G being up to four inches further forward than for the cable rig. Actual LCG values can be found in Appendix A. Figure 11 clearly indicates that the trim angle was responsible for determining whether or not porpoising would occur for a given load. This observation confirms the popular presumption that the inception of porpoising is a function of the geometry of the water flow beneath the boat's hull, due to the running trim angle. In addition to LCG and VCG, the pitch radius of gyration was computed and recorded for each run. The radius of gyration, a popular linear representation of the boat's moment of inertia, measures the weight distribution about the CG. A boat with a greater radius of gyration requires more moment to begin to rotate it about the given centroidal axis.

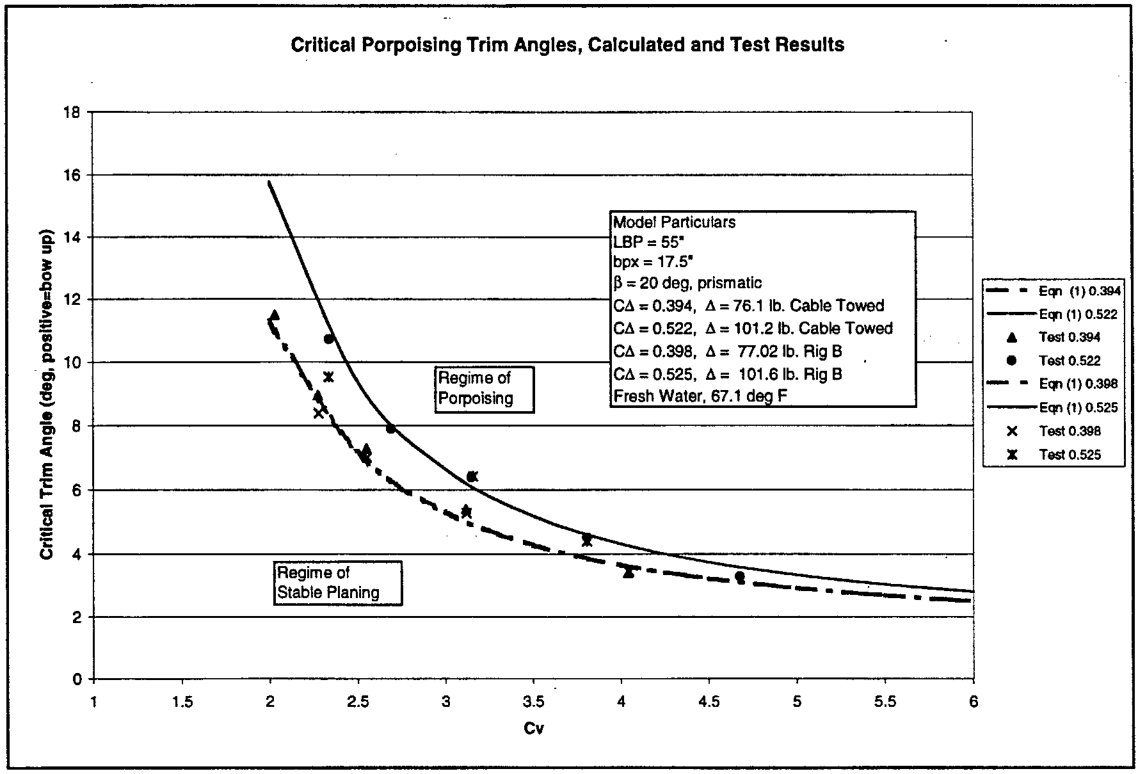


Figure 11 – Experimental Porpoising Inception Boundary for Prismatic Hull Form , $\beta = 20°$

For each run, beginning with the original cable towed runs, the time histories of all data signals were maintained, enabling spectral analysis to be performed on the trim signals for selected runs. By using Quattro Pro's Fourier Analysis function, the oscillations of the model could be broken down into their characteristic frequencies and amplitudes. Because the angle of the propulsive force did not follow the model as it pitched, the rig did not dynamically scale a real boat, but the purpose of the spectral analysis was to quantify the inception of porpoising, and not to measure large motion amplitudes, far beyond inception. The experimenter initially characterized porpoising by "feel" by drawing on experience with full scale planing boats. Because this was not a scientific approach to the problem, the spectral analysis was used to determine for a given test run whether or not porpoising had occurred. By comparing the experience-based pitch amplitude threshold for porpoising inception, with amplitudes determined using spectral analysis, the experimenter concluded that a spectral density equivalent to a one degree amplitude at a given frequency constituted porpoising inception. Quite coincidentally, it was found in Day & Haag's report that they had determined porpoising to begin when the double amplitude of the pitching motion equaled two degrees! This showed that the "gut feel" for the inception of porpoising was similar for different naval architects, separated by 46 years.

When operating just at the boundary of porpoising inception, the model would respond to small waves in the tank by oscillating several times after encountering them.

This motion, no matter how subtle, was immediately distinguishable. If the model encountered several waves in series of the same wavelength, it would produce repeated oscillations similar to porpoising, except that the characteristics of the motion were noticeably different. During testing, wave driven oscillations never appeared to occur exactly at the model's natural porpoising frequency, and when encountering a series of waves, the model would usually impact one harder than the others. Porpoising, on the other hand, produced a smooth motion when just near the inception boundary. For cases that were marginally stable, the motions would die away exponentially, and not become checked as did wave driven oscillations. This discussion pertains to motions on the order of less than one degree, and just perceptible to the trained eye.

A similar, but abbreviated battery of tests was performed for both the 25 and 15 degree deadrise models, using Towing Rig B. The results were plotted in a similar fashion and appear in Figures 12 and 13. The three prismatic hulls performed quite differently, especially when subject to heavy loads.

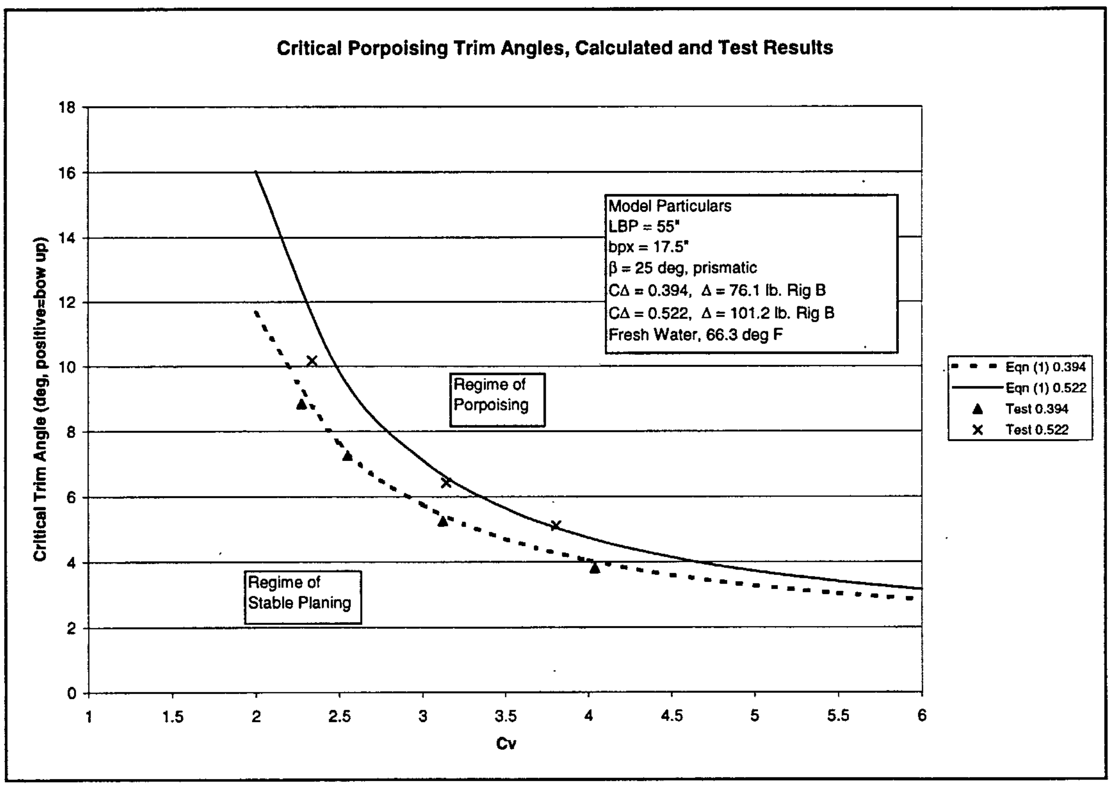


Figure 12 – Experimental Porpoising Inception Boundary for Prismatic Hull Form , $\beta = 25°$

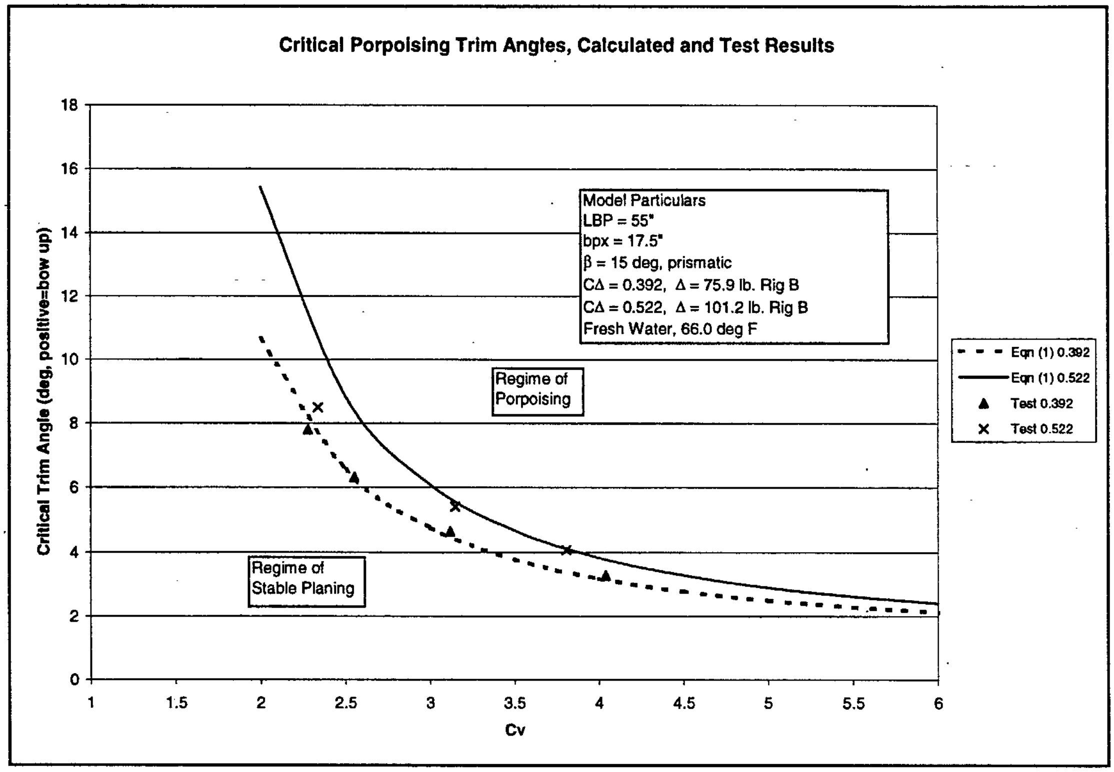


Figure 13 – Experimental Porpoising Inception Boundary for Prismatic Hull Form , $\beta = 15°$

Models of Real Scale Hulls

The purposes of testing the prismatic series were to extend the documented research to higher deadrise angles and to validate the predictive method based on the simple planing shape these hulls projected into the water. Since perfectly prismatic boats are very rare, the next planned step was to expand the testing program to include actual scale hullforms. One of the most important questions the experimenter had in mind from the very beginning of the project was whether or not the stability of a real semi-prismatic hullform, complete with the most common bottom features such as lifting strakes, a keel pad, and a transom notch could be adequately predicted using the same method as for fully prismatic forms. Hull enhancements such as these are usually placed with the intention of improving speed and performance by increasing lift to reduce wetted area and drag.

The first of the two models that was available for this purpose was the 40' NSWC HSAC MKII (High Speed Assault Craft) built to λ=7. This boat is among the most modern of high-deadrise hullforms. Figure 14 and Table 3 below present hull properties.

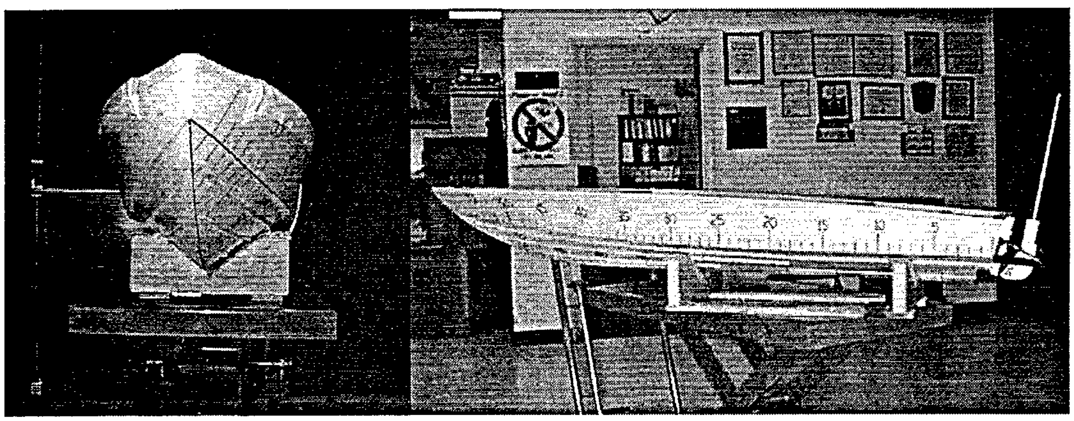


Figure 14 – HSAC MKII Model, $\lambda = 7$.

Table 3 – HSAC MKII Model and Full Scale Parameters

Parameter	Model Value $\lambda = 7$	Full Scale Value
L_{OA}	63 in	36.75 ft
L_{PP}	55.7 in	32.5 ft
B_{PX}	14.28 in	8.33 ft
β	25 degrees	25 degrees
Δ	45.48 to 59.3 lb	16,030 lb to 20,890 lb
LCG	17 to 19.5 in fwd ap	9.9 to 11.4 ft fwd ap
Propulsor	MKII towing rig	2 x MerCruiser Speedmaster Sterndrives
Trim Tabs	4" Scaled K-Planes	30" Kiekhaefer K-planes

It had been determined during testing with the NAHL prismatic series that the porpoising condition could be avoided at any speed achievable in the 380' high-speed tank by progressively moving the CG of the craft forward. In order to achieve stability at the higher speeds, however, the required LCG for all three deadrise hulls was so far forward that the boat would float statically with a negative trim angle (bow down). From experience, no one would ever configure a speedboat in this manner, not just from an aesthetic perspective, but it would cause the boat to be highly dangerous in a following seaway. The potential for submarining would become very great, and the boat could take a great deal of water aboard. During testing in this condition, a safety line made of parachute chord was tied to the bow of the model to prevent submarining from occurring. Since it is not practical to move the CG of a full-scale craft underway, except for very small boats where people are a large fraction of the total load, another means must be implemented to control running trim.

When considering the seakeeping abilities of planing hulls, deadrise is very important. Increased deadrise angles lower the severity of impacts with the water's surface associated with the extreme vertical excursions and possible airborne trajectories which can result from driving the boat fast in heavy seas. While Drs. Sottorf and Savitsky had developed an equation to account for the reduction in lift due to deadrise angle, the question arose of how to evaluate the lifting and porpoising properties of a hull with performance enhancing lifting strakes and reverse chines. As a first approximation, the experimenter chose to characterize the lifting surface with an effective deadrise angle, based on the numerical weighted average of the different deadrise surface areas over the after third of the boat. This method seemed reasonable. Later, it was determined that the lifting strakes and reverse chines actually produced much more lift than predicted by simple methods due to cross flow and flow separation, warranting further analysis and an attempt at modeling the strakes using swept wing lifting theory. It was found that as the loading increased on the model HSAC MKII, the critical porpoising trim angle suggested that the effective deadrise angle was decreasing, possibly due to the increased wetting of the running strakes, which are truncated well forward of the transom. The inboard pair terminate at 27" forward of the transom, the second pair terminate at 19", and the third pair and the reverse chine extend all the way to the transom. Therefore, as more of the forebody of the model comes in contact with the water, the ratio of the strake area to the normal deadrise planing surface increased dramatically. Not only was more lift being produced by the increased running strake area, but the center of pressure of the strake lift was well forward of the center of gravity of the model, producing bow up moment, and further degrading the porpoising stability of the craft.

Approximately seven months prior to testing, a pair of Kiekhaefer 30" K-Planes, shown in Figure 15 were constructed to one-seventh scale. These trim tabs were made of $^{3}/_{32}$" carbon fiber plates and a single stiffener was epoxied down the centerline of each surface, both to cancel any possible deflection under hydrodynamic loads, and to provide a mounting surface for the adjustable turnbuckle. The turnbuckles were intended for installation as suspension links on a high performance radio-controlled car, but were

perfect for the present purpose. They were modified by soldering a nut to the shaft to facilitate manual adjustment while in the water.

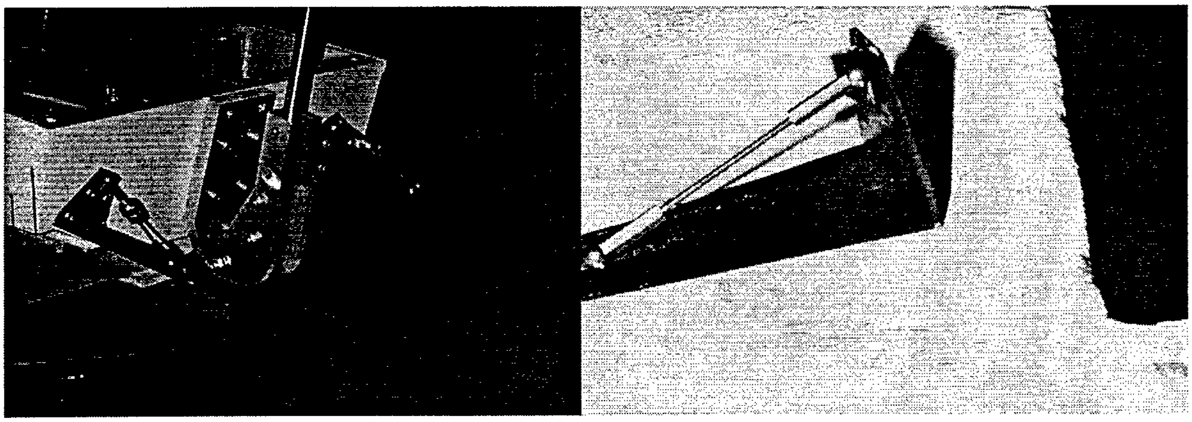


Figure 15 – $\lambda = 7$ Kiekhafer K-Plane Trim Tabs

The experimenter was faced with devising an accurate method for determining and setting the trim tab deflection while the model was attached to the towing rig. After several ideas were evaluated, it was clear that the most reliable and accurate method was to measure the length of the turnbuckle. At each end of the turnbuckle was a ball joint, which was mounted to the carbon fiber flange, and not on the axis of the trim tab's plates. Since the trim tabs had been designed using AUTOCAD LT, it was a simple matter to confirm the actual positions of each turnbuckle, then actually rotate the bottom plate of the trim tab with respect to the transom plate about the hinge axis. AUTOCAD's measure function was used to find the required turnbuckle length for each tab angle. The measurements were regressed in Appendix C and found to be linear within the range of adjustment. Since subtle differences existed in the positions of the mounting holes for each tab's turnbuckle, each tab was analyzed separately. The trim tab deflection was defined as the angle with respect to the local buttock line in the vicinity of the tab. The available range of tab deflections when mounted to this model was –1 to 19 degrees with respect to the water flow.

The K-Planes are mounted to the full-scale hull with a one inch vertical offset, meaning that when trimmed parallel to the bottom of the boat, the step up between the boat's bottom and the trim tab surface is one inch, which ensures that the flow does not attach to the tabs when they are in the retracted position, and not needed. The offset is most easily observed in Figure 1, as the small strip of transom visible between the bottom of the trim tab and the transom/hull bottom intersection. The goal of these experiments was to determine the required tab deflections to achieve stability. Therefore, it was necessary to learn how to quantify not only the force generated by these very low aspect ratio trim tabs acting on the surface of the water in the boat's wake, but also the effects of

installation variations, such as the aforementioned vertical offset, which was expected to produce a reduction in the dynamic pressure acting on the trim tab.

It was immediately apparent that due to the nature of lifting surfaces, the force generated by trim tabs should be a function of the square of the speed of the water across the trim tab. The potential lifting force on four square feet of tab area traveling at full-scale speeds of 100 ft/sec would be very great indeed. Avoiding porpoising at high speeds requires a large bow down moment, and the (negative) bow down moment created by the vertical component of the trim tab lifting force was expected to produce a similar effect. Offshore speedboat operators have long used these large trim tabs to stabilize their boats which are generally configured with multiple heavy engine blocks mounted just forward of the transom, forcing CG extremely far aft.

In addition to the negative trimming moment generated by the tabs, the experimenter expected the magnitude of the lifting force itself to have an effect on the running characteristics of the craft. At high speeds, the trim tabs would have the potential to generate a lifting force equal to almost one quarter of the weight of the craft itself. In order to maintain an equilibrium planing condition, lift produced by trim tabs lessens the planing load the remainder of the hull is expected to carry. Remembering that the loading of the hull is a major factor in the determination of porpoising stability, the experimenter set out to prove from experimentation and calculation that the porpoising stability characteristics would be affected by both the trim moment and the lifting forces produced by the trim tabs.

The testing procedure used to test the HSAC MKII model with trim tabs was as follows: the boat was ballasted to typical NSWC running conditions (Zseleczky, 96). Rather than shifting the position of the center of gravity, as was done for the previous tests, LCG was held constant for each setup, and tests were run at varied speeds and trim tab angles. Initially, the model was run with the trim tabs set at zero deflection, and speed was increased until porpoising occurred. Once operating in the porpoising regime, the trim tab deflection was adjusted on subsequent runs until the porpoising oscillations disappeared completely or were below one degree amplitude, which is just noticeable. The results generally were as expected. Just above the critical porpoising speed for the model without trim tabs, the required trim tab angle to steady the model increased very quickly to the maximum value. As the model was run at higher speeds, less trim tab deflection was required to stabilize the model. This observation was made from full-scale testing data prior to running the model tests, which is the reason it did not come as a surprise. As mentioned earlier, as speed increases, the force imparted by the water on the trim tabs increases as a square function of speed, resulting in the moment produced by the tab "catching up" with the required moment to stabilize the model at high speeds. The normal trends observed during testing of the prismatic series applied to testing the semi-prismatic form with trim tabs as well.

The results of testing with the HSAC MKII model are summarized in Figure 16 and Table 4, which gives the required trim tab deflection for each porpoising inception

point. The predictive curves for this graph were developed by setting the effective deadrise according to the zero tab porpoising inception point, since all other parameters required for the prediction of porpoising trim angle could be predicted. These angles worked out to be 14 degrees for the lightest load through 8 degrees for the heaviest load. The critical porpoising trim angles thus become the "fingerprint" of the hull, allowing its effective deadrise to be determined. In addition, the trim tab deflection was recorded at each critical porpoising point, and the vertical lifting force was calculated, then subtracted from the model's loading coefficient. Equation (1) is still used to calculate the critical porpoising trim angle, except the lift generated by the trim tabs is subtracted, and the effective deadrise value is used. Equation (7) is to be used in conjunction with Equation (1). The load coefficient in the radical of Equation (7) accounts for lift due to trim tabs, and is also referred to as C_δ in this study.

$$\sqrt{\frac{C_L}{2}} = \frac{\sqrt{\dfrac{\Delta - \text{TabLift}}{\rho * g * b^3}}}{C_V} = \sqrt{\frac{C_\delta}{C_V}} \tag{7}$$

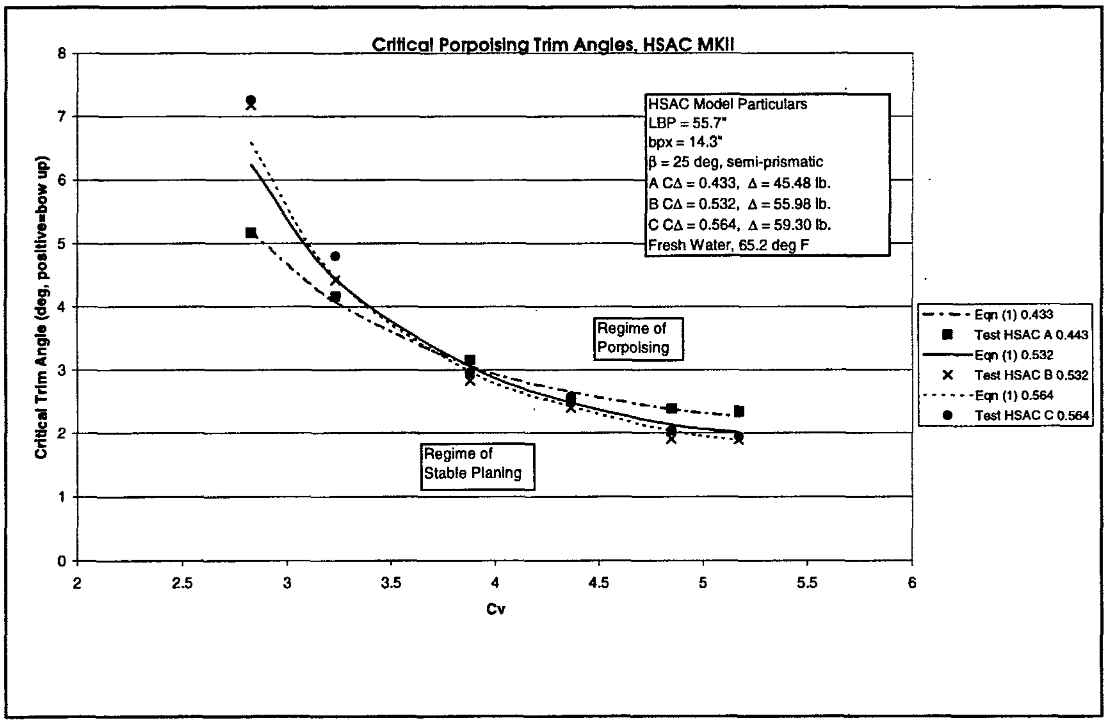


Figure 16 – Experimental Porpoising Inception Boundary for λ=7 HSAC MKII hull form

The load coefficient has been adjusted by subtracting from C_Δ lift generated by the trim tabs from the model's actual weight, and is tabulated under C_δ as given in Equation (7).

V, condition ft/sec	TabDef deg (down)	Cδ	Effective Deadrise
17.5 A	14	0.397	14
20 A	14	0.386	14
24 A	14	0.366	14
27 A	12	0.360	14
30 A	10	0.358	14
32 A	8	0.365	14
17.5 B	4	0.522	10
20 B	14	0.486	10
24 B	18	0.447	10
27 B	19	0.418	10
30 B	18	0.399	10
32 B	15	0.406	10
17.5 C	0	0.564	8
20 C	14	0.518	8
24 C	18	0.479	8
27 C	17	0.462	8
30 C	17	0.438	8
32 C	15	0.438	8

Table 4 –Model Test Data, HSAC MKII

The fifth hullform tested was a λ=9 model of NSWC's 42' jet pump powered boat, given the designation PCC. This boat exhibited prismatic qualities in the after section, but had reverse chines. The hull's deadrise angle was 17.8 degrees, and its pump intakes and outlets had been plugged and faired over for this experiment. The model was run with the trim tabs mounted in the same fashion. The same trim tabs were used, despite the difference in scale factors. This was acceptable because the purpose of these tests was to establish methods for analyzing the properties of the low-aspect ratio trim tabs, and not to make full-scale predictions for a real boat. Towing tank experiments serve as a controlled environment in which analysis can be carried out, and the results define the geometry of the water flow across the model's hull and the movement of the center of pressure with respect to trim angle which ultimately determines porpoising inception.

Testing with the PCC model proceeded in the same manner as for the HSAC MKII. The trim tab turnbuckles were remounted on the tab flanges, and the adjustment procedure was recalibrated to accommodate the 5.1 degree transom rake and the straight buttock lines of the boat. As for the HSAC, the tabs were mounted with a $^1/_8$" vertical offset. A summary of test results for the PCC appears in Figure 17, with trim tab

deflections and effective deadrise angles tabulated in Table 5. After one day of testing with the PCC model, it was determined that the new setup was operating almost exactly as expected. Rather than expand the matrix laterally by running more loading configurations, the opportunity was seized to analyze the effects of altering the trim tabs. The method set forth by Savitsky (1976) predicted trim tab force for high aspect ratio and full beam transom flaps and wedges, but did not appear to represent the lifting qualities of the low aspect ratio, tapered trim tabs in question.

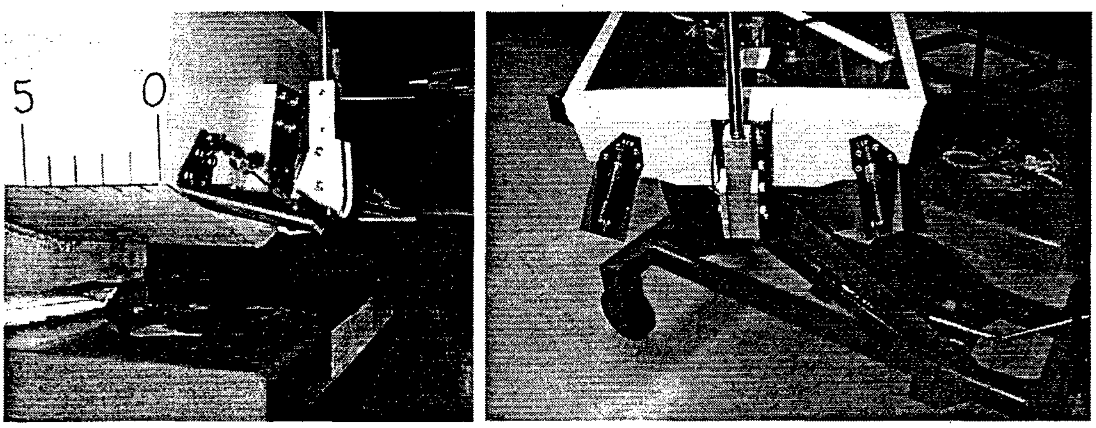


Figure 18 – Trim Tab Modifications

The first modification consisted of simply cutting a pair of plates from $^{1}/_{8}$" thick PVC (polyvinyl chloride, a form of plastic) to the same planform as the trim tabs, and affixing them to the bottom surface of the trim tab with silicone adhesive. This resulted in a zero vertical offset condition, which could be confirmed by placing a ruler along the buttock line and tab combination. The expectation was that at the same deflection angles, the trim tab would produce more lift with the plates attached as the region of lift-robbing low pressure would not exist behind the vertical step up to the trim tab. As anticipated, when the model was run, it required approximately one degree less trim tab deflection at slow speeds, and up to three degrees less deflection at high speeds were required to bring the boat to the same stability condition. Eliminating the vertical mounting offset did in fact increase the pressure under the trim tabs. These tests were performed at the same loading configuration as the original test. The second modification again utilized $^{1}/_{8}$" PVC, except the plates were cut to be rectangles with a 2" width, equivalent to the width of the tapered trim tab at the root. Adding the rectangular plate not only increased the tab area, but the effective aspect ratio as well. Figure 18 shows both trim tab modifications. The database summarizing the results of testing can be found in Appendix A.

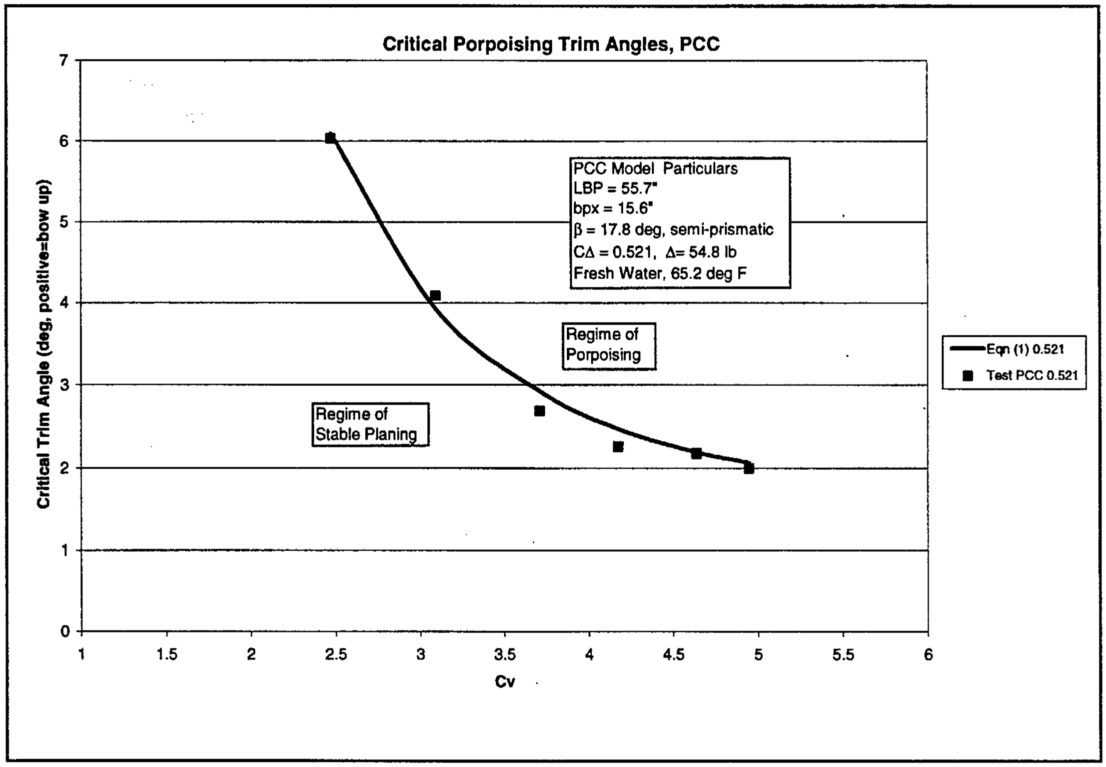


Figure 17 – Results of Testing, PCC

V, condition ft/sec	TabDef deg	Cδ	Effective Deadrise
16, A	14	0.377	12
20, A	15	0.362	12
24, A	15	0.345	12
27, A	15	0.331	12
30, A	13	0.326	12
32, A	11	0.329	12

Table 5 –Model Test Data, PCC

Because of the tapered design of the Kiekhafer trim tabs, there existed a degree of uncertainty as to how to determine their effective aspect ratio as a lifting surface. Up to this point, the experimenter could only draw inference about how much lift was actually being produced from their effects on the stability of the craft. This method depended on the accuracy of several empirically derived equations, most notably the Savitsky Equation 28 (1964) used to predict the center of pressure of the planing surface. This equation clearly did not predict the effects of the lifting strakes. Also, the influence of the hull features forward of the trim tabs could have an effect upon the boundary layer in the region of the trim tabs and/or the flow patterns to the trim tabs themselves. The equations for the center of pressure and trim tab lift could both be adjusted such that they

worked in harmony, but without actually determining the characteristics of one of the forces, both would remain questionable guesses. With such complex influences present, it was clear that in order to develop a reliable method from a scientific approach, a model or full scale test would have to be carried out to determine the trim tab lifting characteristics.

The major requirement for the dynamometry intended for lift measurement was that it would not interfere with the water flow to the trim tabs or produce any extra lift itself. The resulting design is pictured in Figure 19. A 2" force block with a 10 lb. capacity was selected to serve as the force transducer, and an aluminum plate was fabricated to serve as a mounting surface for the port trim tab. The force block was bolted to the top of this plate so that it straddled the transom as shown. A second plate was bolted to the opposite side of the block, and the entire mechanism was bolted through a PVC block to the inside of the transom. The apparatus was shimmed so as to provide approximately 0.02" clearance between the plate and the transom. Therefore, the lift force developed by the trim tab would be transferred completely through the force block for measurement. The apparatus was assembled on the port side, and a $^1/_4$" PVC plate was fabricated and fitted as a spacer on the starboard side to make both sides hydrodynamically similar. The same $^1/_8$" vertical mounting offset was preserved.

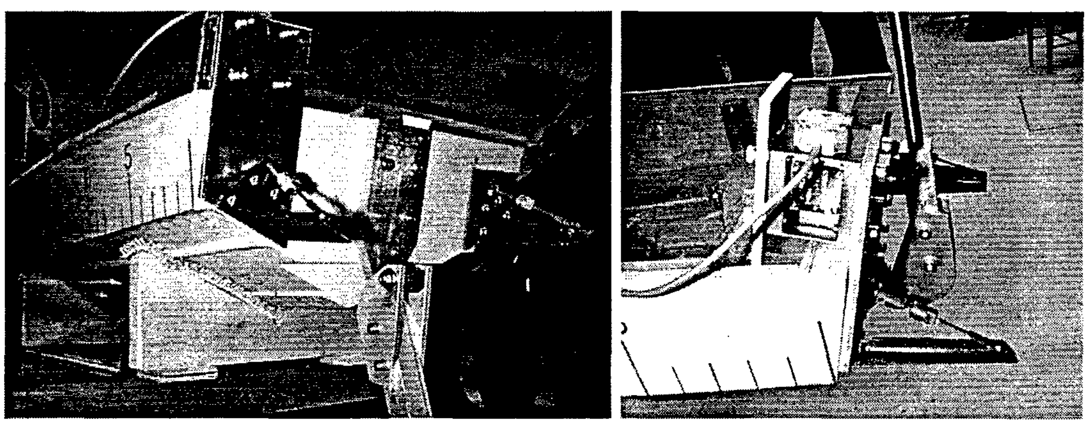


Figure 19 – Trim Tab Lift Dynamometer

Runs were conducted in the standard manner at a variety of speeds. After several runs, it was determined that the lift generated by the measured trim tab was independent of the running trim angle of the HSAC MKII hull, once the rig had accelerated to the fully planing condition. As the model accelerated, the trim tab lift increased exponentially, as expected. As can be seen in Figure 20, the lift time history for this sample run was constant at steady state speed, and then decreased exponentially upon deceleration. The resulting time history of the lift signal appears as a plateau with parabolic sides. It was found that the lift coefficient for all speeds above 17 ft/sec remained essentially constant for each trim tab deflection. Even though the model oscillated several times before settling out, the lift being generated by the trim tab

remained essentially constant. The forces due to pitching accelerations were likely the cause of the small variation that did exist.

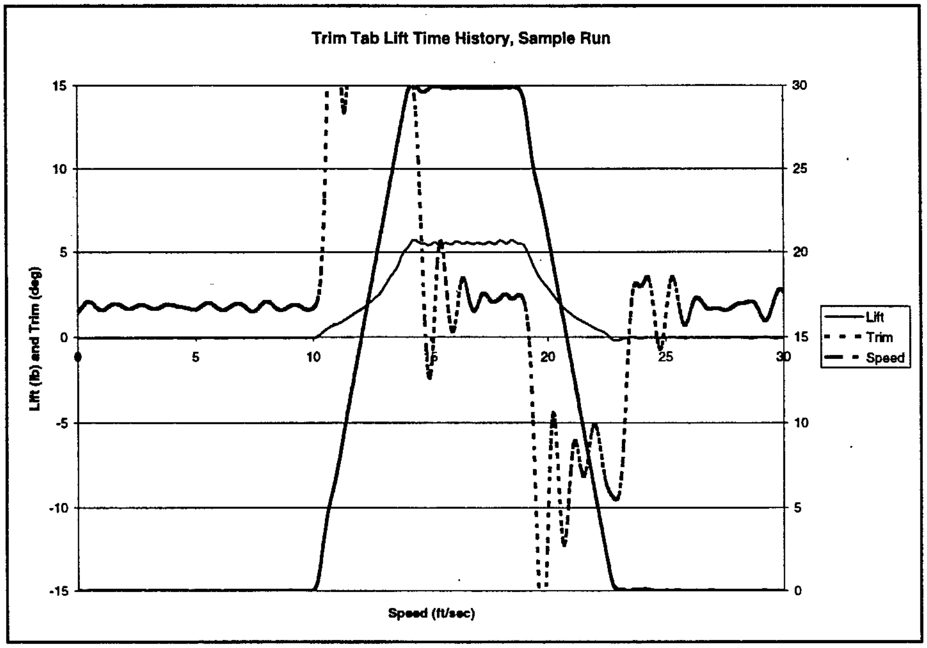


Figure 20 – Sample Time History of Trim Tab Lift Test

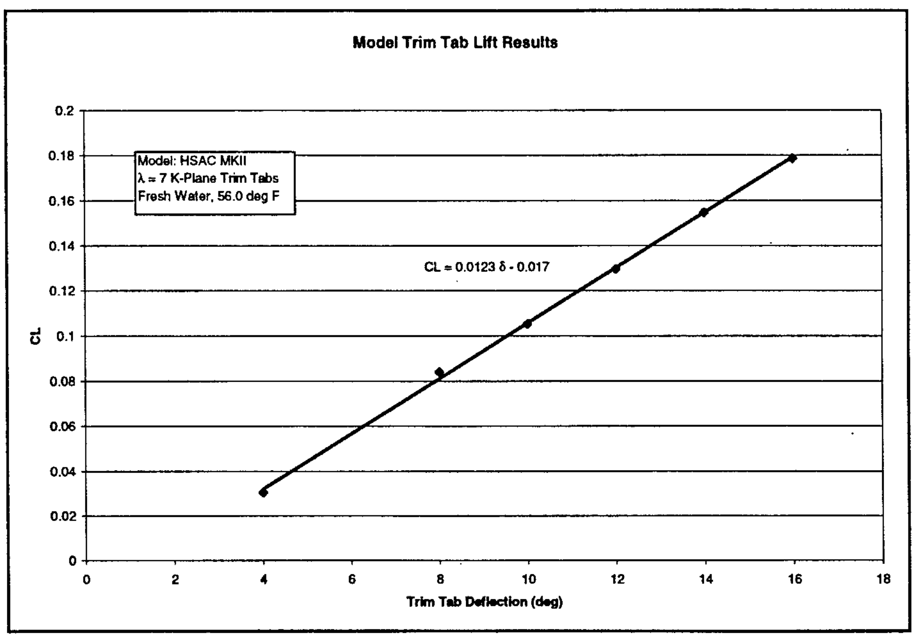


Figure 21 – Lift Coefficient vs. Trim Tab Angle of Attack

Upon compilation of the data, the lift coefficient increment, measured per degree of deflection was also very linear for all deflections above 4 degrees. Figure 21 shows the near-linear character of the lift coefficient data with increasing angle of attack. A linear regression line has been plotted with the points as well, with the equation displayed on the plot. The C_L value appears to occur well above zero degrees tab deflection, and this is believed to be due to the aforementioned vertical mounting offset.

Once the lifting properties of the trim tabs were determined, the next step was to evaluate the existing theoretical methods for calculating lift and select one which would be accurate and suitable for use. Jones' formula predicts the linear lift curve slope for airfoils solely based on the aspect ratio, AR, of the surface. The trim tabs during testing produced a lift curve slope of 0.0123 per degree when measured normal to the trim tab surface, perpendicular to the deadrise surface. When the trim tab span at the one-quarter chord point was used to calculate the aspect ratio, Jones' Formula predicts a lift coefficient of 0.0120 per degree, a difference of 2.5%. This method was adopted for determining the lift produced by low aspect ratio, tapered trim tabs and, since the center of pressure of a lifting surface is generally assumed to be at or very near the one-quarter chord point, it is logical. Equations (8) and (9) are applicable to transom mounted trim tabs for high speed planing hulls.

$$\frac{dC_L}{d\alpha} = \frac{\pi * AR}{2 * 57.3} \quad \text{per degree} \tag{8}$$

$$L_{TAB} = \frac{1}{2}\alpha \frac{dC_L}{d\alpha} \rho V^2 A \tag{9}$$

Summary & Analysis

A total of 247 runs were made in the NAHL 380' towing tank at or near porpoising inception boundaries, with 5 separate model hulls. The load and LCG were varied for the prismatic models, and for the scale models, the trim tab deflection was varied for each displacement setup. All told, the efforts applied to the testing aspect of this program yielded 67 inception points from which to conduct analysis. Equation (1) has been shown to predict the critical porpoising trim angle with a good degree of accuracy for prismatic and semi-prismatic hulls, if the effect of lifting strakes can be accounted for.

The following trends can be observed from the data:

1. Porpoising inception for a given hull at a given speed depends on running trim angle no matter how that trim angle is attained.
2. The critical trim angle increases with increasing deadrise.
3. The critical trim angle increases with increasing loading.
4. The critical trim angle decreases with increasing boat speed.

These observations, while pertinent, do not actually address the significance of the critical trim angle with respect to the natural trim angle the hull would assume for a given speed and loading. Therefore, as a predictive method, knowledge of the critical trim angle is merely a starting point for the ensuing analysis.

After considerable thought, the experimenter determined that in order to determine the running characteristics with respect to the critical running trim angle, every significant force and moment would have to be accounted for, and the system should be in equilibrium. It was clear that such a tool had the potential to become a predictive method itself, but was required to conduct the present analysis. The accuracy of the formulae would determine the potential accuracy of the method, and whether the effects of the trim tabs could be accounted for. Development of this complex spreadsheet was begun using Excel 97, because of the ease with which Macro routines could be created and edited using Visual Basic. Excel's very flexible graphing options would also later allow automatic visual representation of the results. As work progressed on the spreadsheet, Excel's true power was recognized, as it had the ability to make iterative calculations to determine the effect of multiple force additions upon an equilibrium system. The spreadsheet tolerated near-circular references, whereby certain parameters were calculated based upon other parameters that they affected. An example would be causing a slight change to the vertical keel depth, which causes changes in the wetted area, lifting coefficients, and drag, which in turn affects the required thrust, and the lifting forces and moments applied by the propulsive thrust. An equilibrium solution must exist, and the spreadsheet iterates until all forces are balanced, and returns a moment error based upon the critical trim angle for porpoising. Provisions were made in the spreadsheet program for inputting the properties of the hull bottom as discussed earlier, and cells were allocated for the input of loading, propulsive and trim tab parameters.

Formulae for the equilibrium planing conditions were taken from Savitsky's 1964 and 1976 papers, and incorporated into the spreadsheet. An analysis of these formulae indicated that there were several unknowns present, for which there could exist many equilibrium solutions. Equation (1) would serve to eliminate one unknown, the trim angle, and make a solution possible. The logic behind the present solution was to use Equation (1) to predict the critical porpoising trim as a function of speed, placing the hull right on the porpoising inception boundary at evenly spaced speed increments across the applicable speed range. The major unknown remaining was the planing depth of the keel at the transom for each speed increment. The solution was setup by referencing the equations for wetted surface area, lifting coefficients, drag and moments to this planing depth. The necessary dependence of the equations result in the spider web-like flow chart at the end of the section, Figure 22, which graphically represents the operation of the spreadsheet. Excel's Goal Seek function was used to obtain a solution for an individual case. It was set up using one column of the spreadsheet to rectify all forces into the vertical plane, and sum them. This resulted in a "vertical force error," which was then used by the Goal Seek function to adjust the planing depth. When engaged, and viewed on a slow enough computer system, it was possible to actually see the vertical force error oscillate about zero, until it finally converged exactly on zero, yielding the equilibrium condition.

Excel's Macro functions were used to create a routine that would execute the Goal Seek function over the entire speed range. A velocity resolution of C_V=0.25 was used for the solution. The initial results for a sample configuration were presented in the form of a moment error, because of the initial assumption of the critical running trim angle. If the boat would naturally tend to operate at a higher trim angle than the critical angle, it would be unstable with respect to porpoising, and conversely, if it were a stable condition, it would tend toward a running trim angle lower than the critical trim angle. A logic command was used to convert an unstable condition to the negative moment required to reach stability, and for a stable case, the required moment was set to zero. The spreadsheet automatically re-dimensionalized all parameters for final viewing. Any point on Figure 23A faster than 16.5 ft/sec will result in an unstable system, because a negative moment is required to bring the model below its critical trim angle. The required effective horsepower could also be determined for the operating conditions, and the values generated for the bare hull resistance were generally quite close to those measured in previous, unrelated tests. It is necessary to understand that this solution method can only be used as an actual performance predictor at the critical porpoising point trim angle for a given speed, as these are the only points for which the moment error is zero, and actually represent a real point on the hull's performance envelope.

Knowing the required moment to stabilize the boat would be useful, but not nearly as easy to understand as if the program could be designed to calculate the required trim tab deflections based on their compount effect on stability. To do this, another Macro program was devised which automatically iterated through tab deflections from 0 to 19 degrees, and used logic functions to select the critical points from the moment curve produced by each iteration. This presented some difficulty because of the ability to

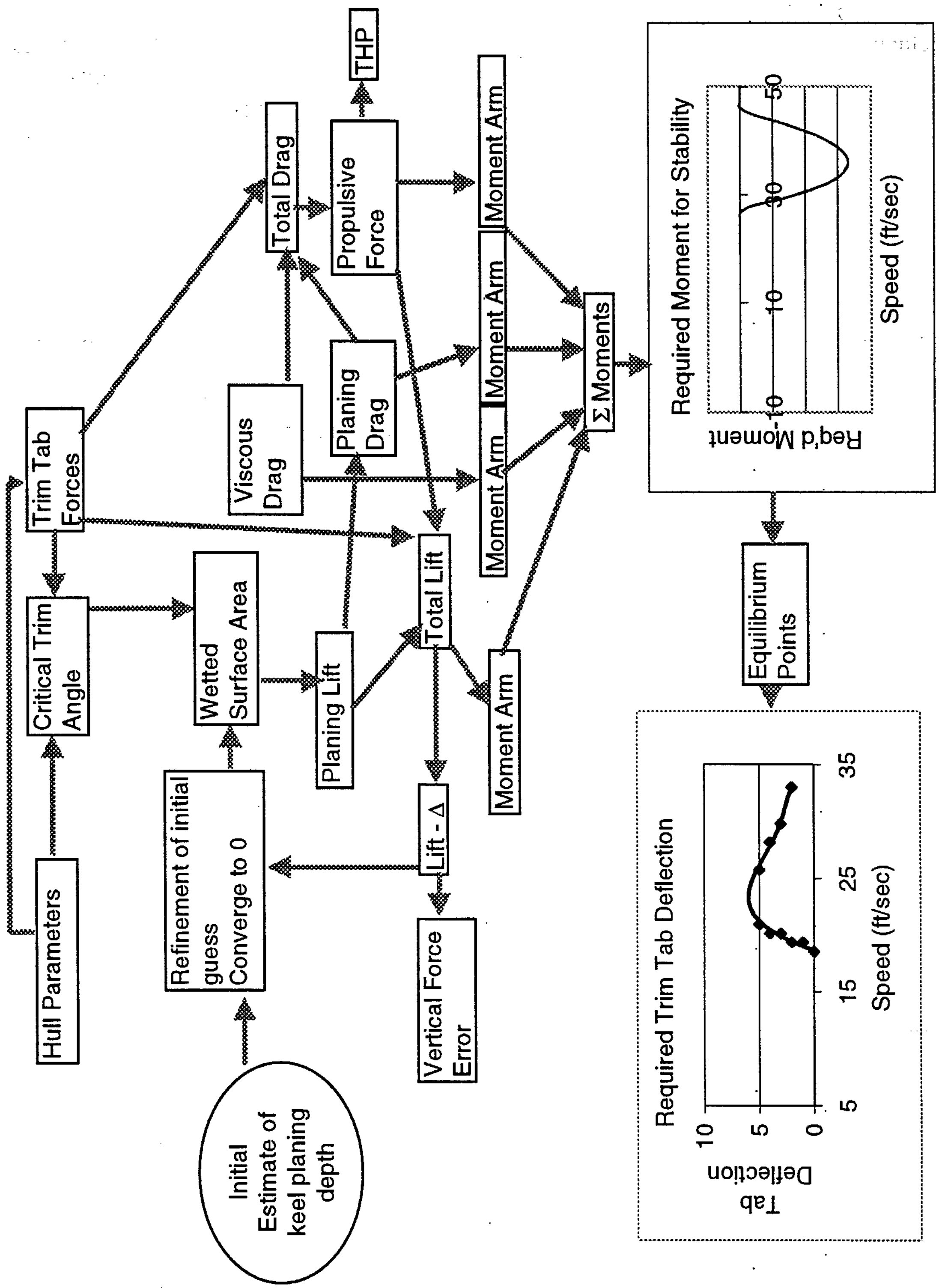


Figure 22 – Spreadsheet Solution Flow Chart

return to stability while increasing speed at a constant trim tab deflection. This was overcome, and the spreadsheet was designed to automatically assemble a plot of the tab deflection required to achieve a given speed, an example of which is shown in Figure 23B. The correlation is easily seen between the two plots, because the point of initial instability for trim tabs set to zero degrees deflection on Figure 23A is at the same speed as the point plotted on 23B. Hence, Figure 23B is merely a cumulation of the critical points from Figure 23A for each trim tab deflection, with a fifth order trendline automatically faired through the points.

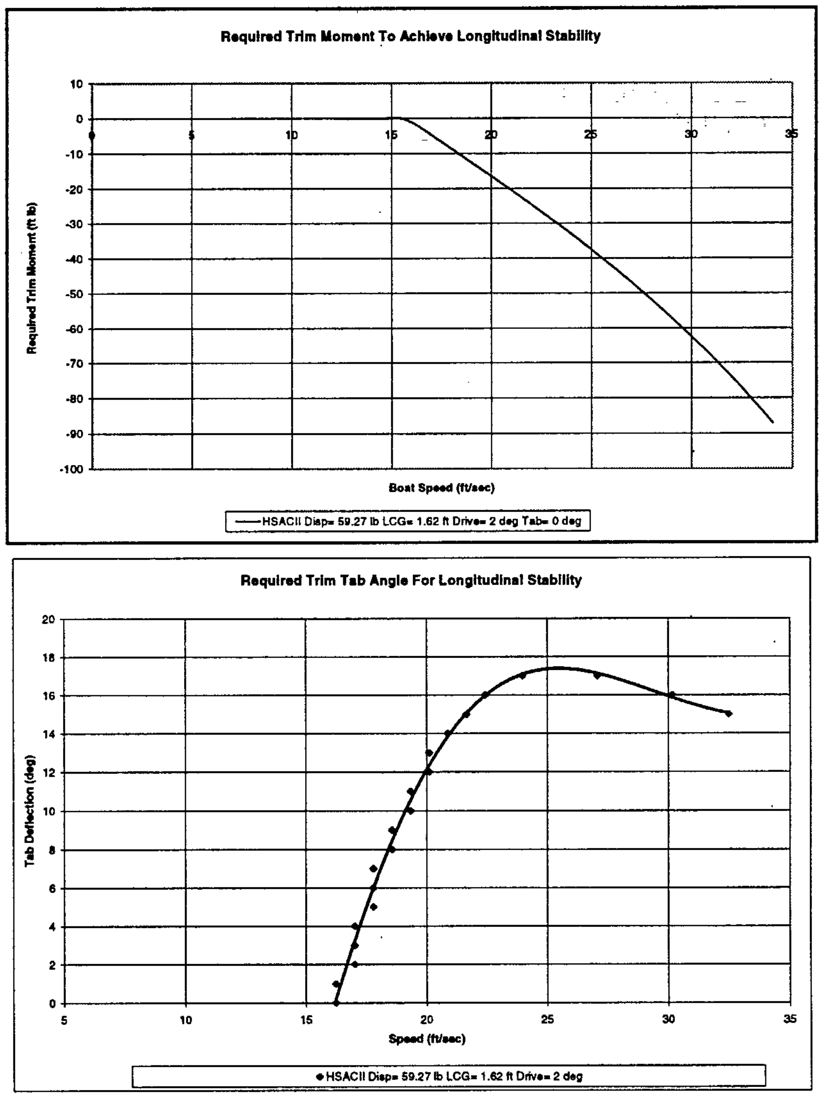


Figure 23A and 23B – Sample Output from Predictive Spreadsheet

Appendix D contains a condensed outline of the spreadsheet program devised to execute the calculations described above. It includes a description of the general layout, logic, and the actual formulas in each cell. Examples of the Macro routines used to perform iterations are included as well.

Conclusions

The present work, testing and analysis has offered a fresh look at the porpoising properties of "V-Hulled" planing boats. The Day & Haag porpoising limits were confirmed using significantly larger models. These results provide confirmation that porpoising is a geometric, pressure related phenomenon. While viscous forces influence the magnitude and direction of the hull resistance force, they do not play a major role in the inception of porpoising. An empirical formula was developed to predict the critical porpoising trim angle. In addition, it was determined that at the porpoising inception limit for a given speed, the critical porpoising trim angle was such that the ratio of hydrodynamically derived support to residual hydrostatic support was very closely preserved regardless of loading or deadrise angle.

During the testing of scale hullforms, it was found that, for purposes of porpoising analysis, the amount of lift provided by running strakes could be quantified by determining the model's porpoising limit. As loading increased, the hull naturally rode deeper in the water, invoking lift from different combinations of running strakes, depending on their shape, transverse location and longitudinal termination point. For a given loading, an effective lifting deadrise angle was determined.

The bulk of testing was performed on scale hulls with adjustable trim tabs. It was found that, once an effective deadrise angle had been established for a given load condition based on the conditions at porpoising with no tab deflection, the critical porpoising trim angle could be determined by using the previously determined formula, subtracting the trim tab lift from the hull's weight. This was done on the assumption that in order to maintain equilibrium, any lift generated by the trim tabs reduces the weight the hull must support. The relatively large magnitude of the lifting forces provided by the tabs did in fact have a profound effect upon the critical trim angle.

To quantify the performance of low-aspect ratio trim tabs, a series of tests was run with a trim tab instrumented to measure the lift being generated. The results of these tests were very logical and several very important relationships were established. First, the magnitude of the lift generated by the trim tabs, once the model was fully planing, was independent of trim angle and any pitching motions. Porpoising motions did not affect the generated lift either, according to the time histories generated by the dynamometry. In addition, the lift generated was a function of the square of the speed, yielding a constant lift coefficient for all fully planing speeds. As predicted by Jones' formula, the lift curve was linear, meaning that the amount of lift generated was linearly related to trim tab deflection for deflections up to 18 degrees. Finally, the slope of this lift curve was within two percent of the slope predicted by Jones' formula, when aspect ratio was taken to be the span of the tab at the one-quarter chord point divided by the chord for the low aspect ratio, tapered trim tabs.

The above lessons and formulas were integrated into an automated prediction method based upon Savitsky's techniques. The computerized solution operated by first

predicting the critical trim angle based on the boat parameters, then basing all calculations on this value and an estimate of keel planing depth. The computer then performs iterations by varying the planing depth, calculating forces and moments, and readjusting the trim angle to match the new conditions. Finally, an equilibrium solution is converged upon. Moments were summed to determine whether or not the boat would tend to operate at a higher or lower trim angle than the assumed critical angle, and a determination of stability made at intervals across the planing speed spectrum. The program was set up to collect the critical points for each trim tab deflection, then present them as a plot of required trim tab angle to achieve stability.

The method presents the designer of high-speed offshore planing boats the ability to assess porpoising stability quickly, and determine whether or not he has chosen large enough trim tabs to suit his hull and center of gravity location. The one shortcoming of this method as developed thus far is that while provision was made for selecting the propulsive force location and angle of application, the effects of actual non-axial propeller forces are not addressed. Predictions were reasonably accurate for towed models, but it cannot be used for a full scale hull until a method is added to it to predict the vertical plane propeller forces generated by various combinations of pitch, rake, and blade and hub design. These forces can be very large for surface piercing propellers. At present there is no known source of such force data in open literature. Preparation is underway to conduct radio-controlled free running stability tests with the λ=7 HSAC MKII hullform. This model is fitted with the same trim tabs used in the towing tank testing, and their deflection is adjustable via radio-control. In addition, the drive trim angle and propeller shaft height of its two outboard engines can be set prior to each run. Electronic radio-telemetry will be used to record the model speed and running trim angle. The effects on propeller forces will be analyzed, and the capability for conducting research at much higher speeds than in the towing tank will be available.

With the increasing importance of littoral warfare to the U.S. Navy, high speed patrol/interdiction craft will become more numerous and more capable. Performance prediction in the design stage will become more necessary for both performance enhancement and affordability. While the traditionally empirical, prototype, test-and-fix approach will continue to be used by the recreational boat and offshore racing boat design communities, a validated, scientifically based prediction tool will prove to be more cost-effective and reliable for the military and commercial high speed craft designs. As sophisticated computation capabilities continue to become available to smaller organizations and individuals, such a tool, when fully validated through full-scale correlation, will hopefully become as widely used and respected as the Day & Haag predictor.

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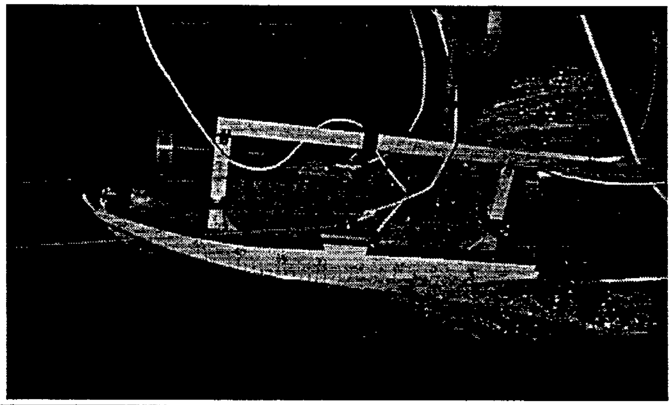
Appendix A

Model Porpoising Inception Testing Data

U.S. Naval Academy Hydromechanics Laboratory

September, 1997 to January, 1998

20 Degree Deadrise Porpoising Test.
Tow Point = 10.9" abl, 27.2" wrt ap
Fresh Water 67.1 deg F

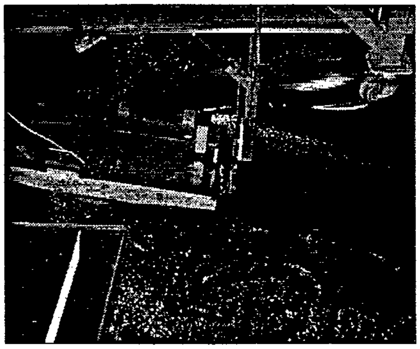


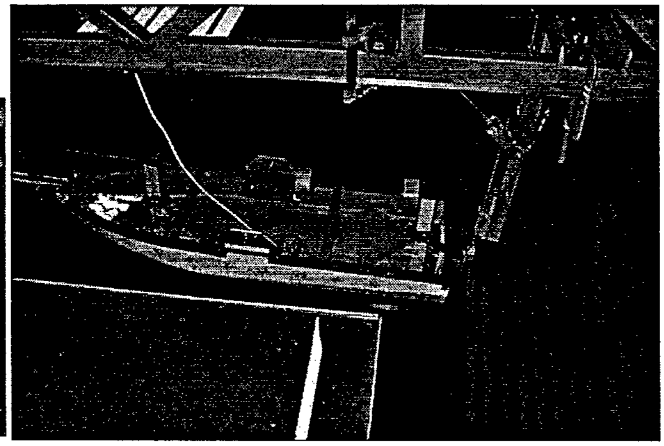
Run #	Time from Prev. Run minutes	Dynamometer Notes	Ave V ft/sec	Ave F lb	Static Trim deg., + bow up	Running Trim	Porp Freq Hz	Spec Dens deg	Wetted Chine inches	Stability Observed
1	1st test	t=2.76	10.02	23.0	2.8	11.2	?	?	?	Stable
2	27.97		15.03	13.3	2.8	7.6	?	?	?	Stable
3	10.41		20.04	13.0	2.8	5.5	2.8125	0.9516	?	Stable
4	1st test	5hz filter t=8.05	13.93	17.3	8.1	11.3	2.8125	0.1732	20.5	Stable
5	17.91		13.93	17.4	8.3	11.4	2.1875	0.8666	20	Porpoise
6	15.13	20hz sample	13.92	17.6	8.5	11.5	1.2500	0.2367	19.5	Slight Porpoise
7	13.83		13.93	17.5	8.8	11.5	1.2500	1.0798	19	Porpoise
8	13.52		15.59	14.6	6.1	9.0	1.2500	0.7262	20.5	Porpoise
9	17.25		15.59	14.3	6.0	9.0	1.2500	0.3782	20.5	Slight Porpoise
10	12.722		15.59	14.2	5.9	8.9	1.2500	0.1905	20	Stable
11	15.11		17.47	12.9	4.6	7.3	1.2500	0.4325	20.25	Slight Porpoise
12	12.12		17.47	12.9	4.5	7.3	1.2500	0.2358	20.5	Stable
13	11.92		21.36	14.4	4.1	5.3	1.2500	2.9622	?	Extreme Porpoise
14	1st Test	t=3.95	21.35	13.0	3.9	5.5	1.5625	2.3248	18	Porpoise
15	16.6		21.35	13.5	3.8	5.5	1.5625	1.9720	18.5	Porpoise
16	16.2		21.35	13.0	3.6	5.5	1.5625	1.2611	19	Porpoise
17	15.78		21.35	13.5	3.5	5.4	1.2500	1.7719	19.5	Porpoise
18	14.91		21.35	13.0	3.2	5.3	1.5625	0.6366	20	Stable
19	20.81		27.69	17.5	2.7	4.0	1.8750	2.9826	18	Porpoise
20	15.9		27.68	17.4	2.5	3.7	1.5625	3.5604	?	Porpoise
21	13.71		27.69	17.6	2.1	3.6	1.5625	3.4289	?	Porpoise
22	16.13		27.69	17.2	1.7	3.6	1.8750	2.1721	20	Porpoise
23	15.93		27.69	17.4	1.3	3.5	1.5625	1.7870	?	Porpoise
24	?	Data Lost	27.68	?	?	?	?	?	18	Stable
25	?		27.69	17.4	0.8	3.4	1.5625	0.4397	18.5	Inception
26	1st Test	t=7.96	14.75	24.1	7.9	11.8	1.2500	0.0908	22.5	Stable
27	12.58		16.03	22.5	7.9	10.7	1.5625	0.8063	21	Inception
28	12.96		17.03	21.4	7.9	10.0	1.5625	2.1159	19.5	Porpoise
29	18.53		21.56	17.7	3.7	6.4	1.5625	0.2349	21.5	Stable
30	15.71		21.57	17.3	4.0	6.4	1.5625	0.8508	20.5	Porpoise
31	16.31		21.57	17.5	4.4	6.5	1.5625	1.5835	19.5	Porpoise
32	74.57	t=2.32	26.09	18.5	2.3	4.5	1.8750	0.3501	19.5	Inception
33	17.91		26.08	18.8	2.6	4.3	1.8750	5.1103	?	Porpoise
34	17.93		26.08	18.4	2.4	4.3	1.8750	2.8155	19.5	Porpoise
35	24.46		26.08	18.5	2.1	4.5	1.8750	0.9353	20	Inception
36	17.36		18.45	18.8	4.8	7.8	1.8750	0.8833	22.5	Slight Porpoise
37	14.58		18.45	18.9	4.5	7.7	1.5625	0.3272	23	Stable
38	19.71		18.44	19.2	5.0	7.9	1.8750	0.3346	21	Inception
39	22.31		32.04	22.8	1.3	3.3	0.9375	0.2179	15	Inception
40	14.13		32.04	23.8	1.6	3.3	2.1875	5.6339	?	Extreme Porpoise

20 Degree Deadrise Porpoising Test.
Tow Point = 10.9" abl, 27.2" wrt ap
Fresh Water 67.1 deg F

Run #	Δ lb	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
1	76.06	0.393	19.99	10.37	24.15	1.71	1.46	0.37
2	76.06	0.393	19.99	10.37	24.15	2.56	2.19	0.16
3	76.06	0.393	19.99	10.37	24.15	3.42	2.93	0.09
4	76.37	0.395	15.09	10.36	21.89	2.37	2.03	0.19
5	76.37	0.395	14.93	10.36	21.82	2.37	2.03	0.19
6	76.37	0.395	14.76	10.36	21.75	2.37	2.03	0.19
7	76.37	0.395	14.60	10.36	21.69	2.37	2.03	0.19
8	76.37	0.395	16.83	10.36	23.00	2.66	2.28	0.15
9	76.37	0.395	16.91	10.36	23.07	2.66	2.28	0.15
10	76.37	0.395	17.00	10.36	23.14	2.66	2.28	0.15
11	76.37	0.395	18.07	10.36	25.03	2.98	2.55	0.12
12	76.37	0.395	18.15	10.36	25.12	2.98	2.55	0.12
13	76.37	0.395	18.74	10.36	24.87	3.64	3.12	0.08
14	76.37	0.395	18.82	10.36	24.96	3.64	3.12	0.08
15	76.37	0.395	18.90	10.36	25.06	3.64	3.12	0.08
16	76.37	0.395	19.07	10.36	25.25	3.64	3.12	0.08
17	76.37	0.395	19.23	10.36	25.45	3.64	3.12	0.08
18	76.37	0.395	19.56	10.36	25.86	3.64	3.12	0.08
19	76.37	0.395	19.90	10.36	24.00	4.72	4.04	0.05
20	76.37	0.395	20.23	10.36	24.41	4.72	4.04	0.05
21	76.37	0.395	20.73	10.36	25.05	4.72	4.04	0.05
22	76.37	0.395	21.23	10.36	24.35	4.72	4.04	0.05
23	76.37	0.395	21.73	10.36	25.03	4.72	4.04	0.05
24	76.37	0.395	22.56	10.36	?	?	4.04	?
25	76.37	0.395	22.32	10.36	22.73	4.72	4.04	0.05
26	101.17	0.523	16.43	8.66	15.58	2.40	2.15	0.23
27	101.17	0.523	16.43	8.66	15.58	2.61	2.34	0.19
28	101.17	0.523	16.43	8.66	15.58	2.77	2.49	0.17
29	101.17	0.523	20.18	8.66	17.76	3.51	3.15	0.11
30	101.17	0.523	19.87	8.66	18.18	3.51	3.15	0.11
31	101.17	0.523	19.56	8.66	16.93	3.51	3.15	0.11
32	101.17	0.523	21.24	8.66	18.02	4.24	3.81	0.07
33	101.17	0.523	20.93	8.66	18.38	4.24	3.81	0.07
34	101.17	0.523	21.12	8.66	18.16	4.24	3.81	0.07
35	101.17	0.523	21.46	8.66	18.29	4.24	3.81	0.07
36	101.17	0.523	18.93	8.66	16.98	3.00	2.69	0.14
37	101.17	0.523	19.18	8.66	17.28	3.00	2.69	0.14
38	101.17	0.523	18.68	8.66	16.71	3.00	2.69	0.14
39	101.17	0.523	22.19	8.66	17.14	5.21	4.68	0.05
40	101.17	0.523	21.94	8.66	17.04	5.21	4.68	0.05

20 Degree Deadrise Porpoising Test.
Tow Point = 1.6" abl, -1' wrt ap
Fresh Water, 67.1 deg F



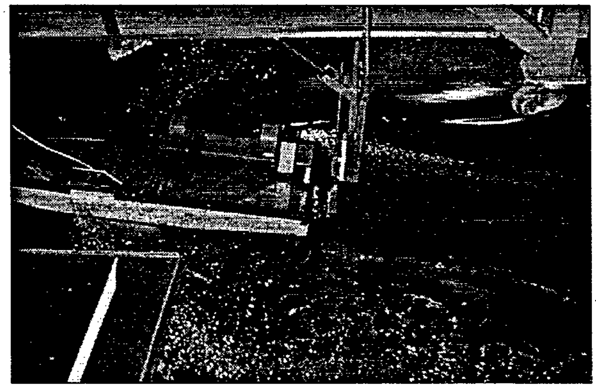


Run #	Time from Prev. Run minutes	Dynamometer Notes	Ave V ft/sec	Running Trim deg + up	Porp Freq Hz	Spec Dens deg	Rod Trim Angle deg + up	Wetted Chine inches	Stability Observed
43	1st Test	t=4.87	13.95	9.3	0.9375	0.66	0.00		Slight Porpoise
44	14.25		15.03	8.3	0.9375	0.32	8.32	21	Stable
45	14.25		17.50	6.6	1.2500	2.13	7.30	19.75	Stable
46	13.90		21.38	4.5	1.5625	0.28	5.49	20.5	Stable
47	13.83		21.39	4.6	1.5625	0.66	5.49	18.5	Slight Porpoise
48	12.50		21.39	4.6	1.5625	6.06	5.49	?	Extreme Porpoise
49	11.26		21.38	4.8	1.5625	4.05	5.00	22.5	Poropise
50	15.73	t=3.27, new rig	15.02	9.0	1.5625	0.11	5.00	?	Stable
51	14.45		21.38	5.3	1.5625	5.95	5.00	?	Porpoise- Block hit stop
52	1st Test	t=5.00	15.62	7.8	1.2500	7.95	5.00	?	Porpoise
53	15.55		15.62	8.5	1.2500	7.58	8.90	?	Porpoise
54	12.82		15.61	8.6	1.2500	4.59	8.90	20	Porpoise
55	13.25		15.61	8.4	0.9375	0.36	8.90	20	Inception
56	14.78		17.50	7.0	1.2500	1.87	7.30	20	Porpoise
57	11.36		17.50	7.0	1.2500	1.75	7.30	21	Inception
58	15.25		21.38	5.3	1.5625	1.99	5.50	18	Slight Porpoise
59	10.23		21.39	5.3	1.5625	0.91	5.50	19	Inception
60	12.53		27.72	3.8	1.8750	5.78	3.50	?	Porpoise
61	11.07		27.72	3.8	1.8750	4.73	3.50	?	Porpoise
62	11.51		27.73	3.4	1.8750	7.12	3.50	?	Porpoise
63	12.31		27.72	3.3	1.8750	5.45	3.50	?	Porpoise
64	11.18		27.72	3.4	1.5625	1.40	3.50	17	Inception
65	30.95	t=3.68	16.02	?	?	?	10.00	?	Extreme Porpoise
66	15.45	t=5.20	16.02	?	?	?	10.00	?	Porpoise
67	15.20	t=4.38	16.02	9.5	1.2500	8.74	10.00	?	Porpoise
68	11.33		16.02	9.5	1.2500	0.60	10.00	22	Inception
69	16.88		21.65	6.7	1.2500	7.83	10.00	?	Porpoise
70	16.25		21.66	6.6	1.2500	7.68	6.40	?	Porpoise
71	10.67		21.58	6.2	1.5625	8.57	6.40	?	Porpoise
72	9.25		21.64	6.5	1.2500	1.00	6.40	23	Inception
73	12.07		26.08	4.4	1.8750	6.37	4.25	?	Porpoise
74	8.48		26.07	4.4	1.8750	5.43	4.25	20	Porpoise
75	7.21		26.08	4.1	1.8750	6.54	4.25	?	Porpoise
76	7.13		26.07	4.0	1.8750	5.66	4.25	?	Porpoise
77	7.00		26.08	4.1	1.8750	1.35	6.50	22.5	Inception

20 Degree Deadrise Porpoising Test.
Tow Point = 1.75" abl, -1' wrt ap
Fresh Water, 67.1 deg F

Run #	Δ lb	LCG in fwd ap	VCG in abl	K in	CDelta	VolFn	Cv	CL
43	75.94	18.90	8.72	15.50	0.392	2.38	2.04	0.19
44	76.16	19.04	8.72	15.69	0.393	2.56	2.19	0.16
45	76.16	19.04	8.72	15.69	0.393	2.99	2.56	0.12
46	76.16	21.04	8.72	16.18	0.393	3.65	3.12	0.08
47	76.16	20.04	8.72	15.78	0.393	3.65	3.12	0.08
48	76.16	19.04	8.72	15.69	0.393	3.65	3.12	0.08
49	76.16	19.54	8.72	15.69	0.393	3.65	3.12	0.08
50	77.04	18.74	8.57	15.49	0.398	2.56	2.19	0.17
51	77.04	19.56	8.57	15.54	0.398	3.64	3.12	0.08
52	77.04	17.35	8.59	16.21	0.398	2.66	2.28	0.15
53	77.04	17.35	8.59	16.21	0.398	2.66	2.28	0.15
54	77.04	18.34	8.59	15.92	0.398	2.66	2.28	0.15
55	77.04	18.99	8.59	15.89	0.398	2.66	2.28	0.15
56	77.04	19.65	8.59	16.00	0.398	2.98	2.55	0.12
57	77.04	19.98	8.59	16.11	0.398	2.98	2.55	0.12
58	77.04	20.63	8.59	16.42	0.398	3.64	3.12	0.08
59	77.04	20.96	8.59	16.62	0.398	3.64	3.12	0.08
60	77.04	22.28	8.59	17.72	0.398	4.72	4.05	0.05
61	77.04	22.69	8.59	17.38	0.398	4.72	4.05	0.05
62	77.04	23.18	8.59	17.02	0.398	4.72	4.05	0.05
63	77.04	24.00	8.59	16.58	0.398	4.72	4.05	0.05
64	77.04	24.66	8.59	16.37	0.398	4.72	4.05	0.05
65	101.59	17.23	6.46	15.34	0.525	2.60	2.34	0.19
66	101.53	18.27	7.13	14.68	0.525	2.60	2.34	0.19
67	101.59	19.01	7.13	15.09	0.525	2.60	2.34	0.19
68	101.59	19.75	7.13	15.56	0.525	2.60	2.34	0.19
69	101.53	20.20	7.13	15.06	0.525	3.52	3.16	0.11
70	101.53	20.89	7.13	15.83	0.525	3.52	3.16	0.10
71	101.53	21.57	7.13	15.30	0.525	3.51	3.15	0.11
72	101.53	22.57	7.13	14.90	0.525	3.52	3.16	0.11
73	101.53	23.32	7.13	14.90	0.525	4.24	3.81	0.07
74	101.53	23.82	7.13	15.05	0.525	4.24	3.81	0.07
75	101.53	24.31	7.13	15.31	0.525	4.24	3.81	0.07
76	101.53	24.81	7.13	15.68	0.525	4.24	3.81	0.07
77	101.53	24.81	7.13	15.68	0.525	4.24	3.81	0.07

25 Degree Deadrise Porpoising Test.
Tow Point = 2" abl, -1' wrt ap
Fresh Water 66.3 deg F

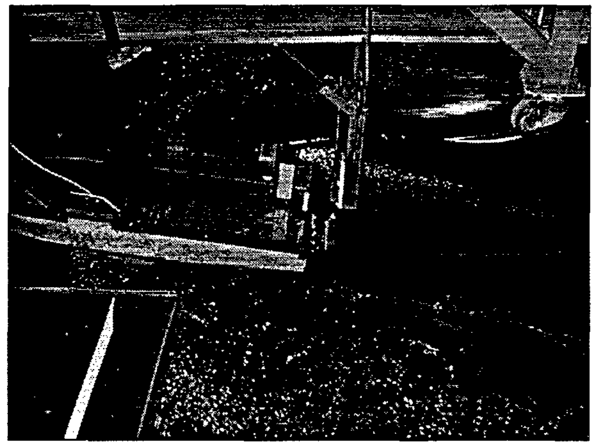


Run #	Time from Prev. Run minutes	Dyn Notes	Ave V ft/sec	Running Trim deg + up	Porp Freq Hz	Spec Dens Deg	Rod Trim Angle deg + up	Wetted Chine inches	Stability Observed
78	1st Test	t=3.31	15.58	8.3	1.5625	0.186	8.90	20.5	Stable
79	10.21		15.58	8.9	1.5625	0.166	8.90	19	Inception
80	10.55		15.58	9.0	1.2500	5.881	8.90	?	Porpoise
81	13.7		17.47	7.0	1.2500	0.198	7.30	20	Stable
82	10.83		17.47	7.4	1.2500	0.206	7.30	18	Stable
83	11.7		17.47	7.3	1.2500	0.226	7.30	18	Stable
84	12.58		17.47	7.4	1.2500	7.974	7.30	?	Porpoise
85	17.48		21.37	5.4	1.5625	4.257	5.50	17	Porpoise
86	9.4		21.40	5.3	1.5625	1.038	5.50	17.5	Inception
87	10.45		21.39	5.2	1.5625	0.288	5.50	17.5	Stable
88	15.68		27.67	3.7	1.8750	0.539	3.50	16	Stable
89	9.12		27.67	3.8	1.8750	2.556	3.50	?	Porpoise
90	20.15		27.67	3.8	1.8750	1.117	3.50	16	Inception
91	1st Test	t=5.21	16.01	10.4	1.2500	8.044	10.00	?	Extreme Porpoise
92	10.35		16.01	10.2	0.9375	0.921	10.00	23	Inception
93	13.3	t=2.60	21.58	6.1	1.5625	5.961	6.40	?	Extreme Porpoise
94	12.26		21.55	6.4	1.2500	0.586	6.40	20.5	Stable
95	11.16		21.55	6.4	1.2500	0.673	6.40	?	inception
96	11.67		26.07	5.1	1.8750	0.654	4.25	19.75	Stable
97	9.48		26.07	5.1	1.5625	2.812	4.25	?	Porpoise
98	8.97		26.07	5.0	1.8750	3.440	4.25	?	Extreme Porpoise

25 Degree Deadrise Porpoising Test.
Tow Point = 2" abl, -1' wrt ap
Fresh Water 66.3 deg F

Run #	Δ lb	LCG in fwd ap	VCG in abl	K in	CDelta	VolFn	Cv	CL
78	76.30	19.49	8.60	16.89	0.394	2.66	2.27	0.15
79	76.30	18.50	8.60	16.71	0.394	2.66	2.27	0.15
80	76.30	18.00	8.60	16.74	0.394	2.66	2.27	0.15
81	76.30	20.32	8.60	17.26	0.394	2.98	2.55	0.12
82	76.30	19.33	8.60	16.84	0.394	2.98	2.55	0.12
83	76.30	18.83	8.60	16.74	0.394	2.98	2.55	0.12
84	76.30	18.33	8.60	16.71	0.394	2.98	2.55	0.12
85	76.30	20.65	8.60	17.46	0.394	3.64	3.12	0.08
86	76.30	21.32	8.60	17.95	0.394	3.65	3.12	0.08
87	76.30	21.81	8.60	18.39	0.394	3.65	3.12	0.08
88	76.30	23.64	8.60	17.46	0.394	4.72	4.04	0.05
89	76.30	22.64	8.60	18.03	0.394	4.72	4.04	0.05
90	76.30	23.14	8.60	17.71	0.394	4.72	4.04	0.05
91	100.95	18.95	7.18	14.99	0.522	2.61	2.34	0.19
92	100.95	20.20	7.18	15.84	0.522	2.61	2.34	0.19
93	100.95	20.82	7.18	16.50	0.522	3.51	3.15	0.11
94	100.95	21.83	7.18	15.79	0.522	3.51	3.15	0.11
95	100.95	22.20	7.18	15.64	0.522	3.51	3.15	0.11
96	100.95	23.21	7.18	15.53	0.522	4.24	3.81	0.07
97	100.95	22.58	7.18	15.54	0.522	4.24	3.81	0.07
98	100.95	22.89	7.18	15.51	0.522	4.24	3.81	0.07

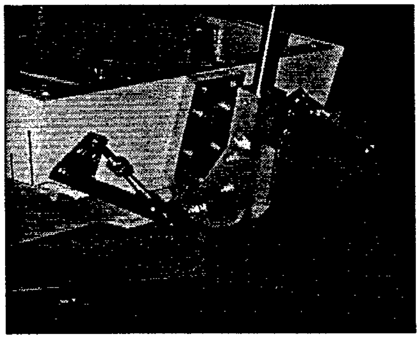
15 Degree Deadrise Porpoising Test.
Tow Point = 1.5" abl, -1' wrt ap
Fresh Water, 66 deg F

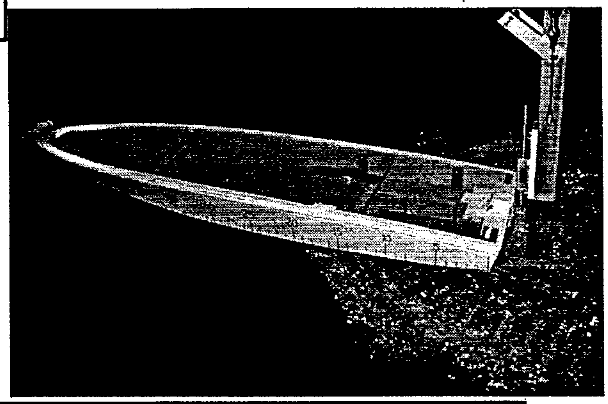


Run #	Time from Prev. Run minutes	Dyn Notes	Ave V ft/sec	Running Trim deg + up	Porp Freq Hz	Spec Dens deg	Rod Trim Angle deg + up	Wetted Chine inches	Stability Observed
99	1st Test	t=3.10	15.61	7.59	1.5625	0.19	8.9	22	Stable
100	11.13		15.61	7.84	1.2500	7.69	8.9	?	Porpoise
101	12.45	t=3.39	15.61	7.80	0.9375	0.26	8.9	20.5	Inception
102	9.96		17.49	6.47	1.2500	0.54	7.3	21	inception
103	10.51		17.49	6.31	1.2500	0.62	7.3	22	Stable
104	9.58		17.49	6.33	1.2500	0.89	6.3	22	inception
105	12.51		21.37	4.67	1.5625	3.31	5.5	?	Porpoise
106	9.58		21.37	4.53	1.5625	0.31	5.5	22.5	Stable
107	10.2		21.37	4.64	1.5625	1.03	5.5	22	Inception
108	9.58		27.67	3.29	1.8750	1.02	3.5	?	Porpoise
109	8.3		27.68	3.27	1.8750	1.82	3.5	20	Slight Porpoise
110	8.41		27.68	3.30	1.8750	1.03	3.5	20	Inception
111	25.66		16.02	9.21	1.2500	4.98	10	?	Extreme Porpoise
112	10.4		16.02	8.71	1.2500	4.07	10	?	Porpoise
113	9.5		16.02	8.50	1.5625	0.38	10	20	Stable
114	12.13		21.59	5.38	1.5625	6.87	6.4	?	Porpoise
115	8.69		21.58	5.41	1.8750	0.90	6.4	25	Inception
116	8.56		26.08	4.17	1.5625	2.52	4.25	?	Porpoise
117	8.76		26.08	4.07	1.8750	1.16	4.25	24	Inception

Run #	Δ lb	LCG in fwd ap	VCG in abl	K in	CDelta	VolFn	Cv	CL
99	75.87	19.44	8.04	16.87	0.392	2.66	2.28	0.15
100	75.87	18.44	8.04	16.74	0.392	2.66	2.28	0.15
101	75.87	18.94	8.04	16.77	0.392	2.66	2.28	0.15
102	75.87	19.94	8.04	17.04	0.392	2.99	2.55	0.12
103	75.87	20.44	8.04	17.28	0.392	2.98	2.55	0.12
104	75.87	20.44	8.04	17.28	0.392	2.98	2.55	0.12
105	75.87	21.78	8.04	18.25	0.392	3.65	3.12	0.08
106	75.87	22.74	8.04	18.07	0.392	3.65	3.12	0.08
107	75.87	22.23	8.04	18.45	0.392	3.65	3.12	0.08
108	75.87	23.40	8.04	17.66	0.392	4.72	4.04	0.05
109	75.87	23.90	8.04	17.43	0.392	4.72	4.04	0.05
110	75.87	24.40	8.04	17.26	0.392	4.72	4.04	0.05
111	100.98	20.11	8.15	16.97	0.521746	2.61	2.34	0.19
112	100.98	20.86	8.15	17.51	0.521746	2.61	2.34	0.19
113	100.98	21.58	8.15	17.82	0.521746	2.61	2.34	0.19
114	100.98	22.96	8.15	17.12	0.521746	3.51	3.15	0.11
115	100.98	23.97	8.15	17.10	0.521746	3.51	3.15	0.11
116	100.98	24.47	8.15	17.24	0.521746	4.24	3.81	0.07
117	100.98	24.97	8.15	17.48	0.521746	4.24	3.81	0.07

HSAC A Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 65.2 deg F



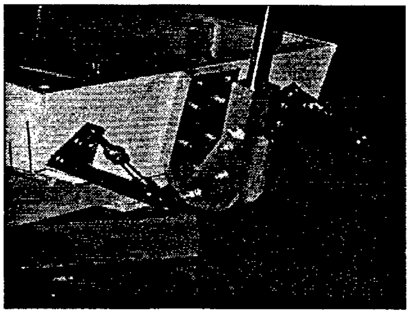


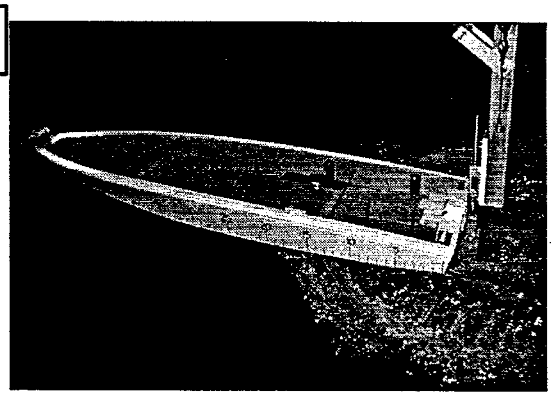
Run #	Time from Prev. Run minutes	Ave V ft/sec	Trim Tab Deflection deg, + dn	Running Trim deg, + up	Rod Trim Angle deg, + up	Wetted Chine inches	Wetted Keel inches	Stability Observed
118	1st Run	7.01	0	7.16	3.5	?	?	Stable
119	8.15	15.52	0	7.09	3.5	18	32	Stable
120	11.36	20.03	0	?	3.5	?	?	Porpoise
121	16.66	20.03	2	?	3.5	?	?	Porpoise
122	11.95	20.03	4	?	3.5	?	?	Porpoise
123	12.23	20.03	6	?	3.5	?	?	Porpoise
124	8.93	20.03	8	?	3.5	?	?	Slight Porpoise
125	10.78	20.03	10	4.73	4.5	16	?	Slight Porpoise
126	8.33	20.04	12	4.49	4.5	15	35	Inception
127	12.18	20.04	14	4.17	4.5	15	37	Stable
128	1st Run	24.06	14	3.00	4.5	8	40	Stable
129	14.00	24.04	10	?	4.5	?	?	Porpoise
130	8.90	24.04	12	?	4.5	?	?	Porpoise
131	6.11	24.03	12	3.36	4.5	?	?	Porpoise
132	6.05	27.04	12	2.81	4.5	?	?	Porpoise
133	5.71	27.04	12	2.84	4.5	?	?	Porpoise
134	9.53	27.04	14	2.48	4.5	18	46	Stable
135	6.21	30.04	14	2.06	4.5	?	47	Stable
136	7.11	30.05	12	2.14	4.5	11	47	Stable
137	5.78	30.04	12	2.28	4.5	11	47	Stable
138	10.16	30.04	10	2.46	4.5	?	?	Porpoise
139	7.38	30.04	11	2.36	4.5	10	46	Inception
140	5.43	32.04	11	2.14	4.5	9	?	Stable
141	7.28	32.04	10	2.18	4.5			Stable
142	12.53	32.04	9	2.33	4.5	9	?	Inception
143	6.03	32.04	8	2.43	4.5	?	?	Porpoise
144	5.30	17.52	8	5.65	4.5	?	?	Porpoise
145	10.31	17.52	12	5.35	4.5	?	?	Porpoise
146	6.30	17.52	14	5.17	4.5	?	?	Stable

HSAC A Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 65.2 deg F

Run #	Δ lb	CDelta	Calc Tab Lift	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
118	45.47	0.432	0.00	0.432	17.37	4.62	19.08	1.30	1.13	0.674
119	45.47	0.432	0.00	0.432	17.37	4.62	19.08	2.88	2.51	0.137
120	45.47	0.432	0.00	0.432	17.37	4.62	19.08	3.72	3.24	0.083
121	45.47	0.432	0.69	0.426	17.37	4.62	19.08	3.72	3.24	0.083
122	45.47	0.432	1.37	0.419	17.37	4.62	19.08	3.72	3.24	0.083
123	45.47	0.432	2.06	0.413	17.37	4.62	19.08	3.72	3.24	0.083
124	45.47	0.432	2.75	0.406	17.37	4.62	19.08	3.72	3.24	0.083
125	45.47	0.432	3.43	0.400	17.37	4.62	19.08	3.72	3.24	0.083
126	45.47	0.432	4.12	0.393	17.37	4.62	19.08	3.72	3.24	0.082
127	45.47	0.432	4.81	0.387	17.37	4.62	19.08	3.72	3.24	0.082
128	45.47	0.432	6.94	0.366	17.37	4.62	19.08	4.47	3.89	0.057
129	45.47	0.432	4.95	0.385	17.37	4.62	19.08	4.47	3.89	0.057
130	45.47	0.432	5.94	0.376	17.37	4.62	19.08	4.47	3.89	0.057
131	45.47	0.432	5.93	0.376	17.37	4.62	19.08	4.47	3.88	0.057
132	45.47	0.432	7.51	0.361	17.37	4.62	19.08	5.03	4.37	0.045
133	45.47	0.432	7.51	0.361	17.37	4.62	19.08	5.03	4.37	0.045
134	45.47	0.432	8.76	0.349	17.37	4.62	19.08	5.03	4.37	0.045
135	45.47	0.432	10.81	0.330	17.37	4.62	19.08	5.58	4.86	0.037
136	45.47	0.432	9.27	0.344	17.37	4.62	19.08	5.59	4.86	0.037
137	45.47	0.432	9.27	0.344	17.37	4.62	19.08	5.58	4.86	0.037
138	45.47	0.432	7.72	0.359	17.37	4.62	19.08	5.58	4.86	0.037
139	45.47	0.432	8.50	0.352	17.37	4.62	19.08	5.58	4.86	0.037
140	45.47	0.432	9.67	0.340	17.37	4.62	19.08	5.95	5.18	0.032
141	45.47	0.432	8.79	0.349	17.37	4.62	19.08	5.95	5.18	0.032
142	45.47	0.432	7.91	0.357	17.37	4.62	19.08	5.95	5.18	0.032
143	45.47	0.432	7.03	0.366	17.37	4.62	19.08	5.95	5.18	0.032
144	45.47	0.432	2.10	0.412	17.37	4.62	19.08	3.26	2.83	0.108
145	45.47	0.432	3.15	0.402	17.37	4.62	19.08	3.26	2.83	0.108
146	45.47	0.432	3.68	0.397	17.37	4.62	19.08	3.26	2.83	0.108

HSAC B Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 65.0 deg F

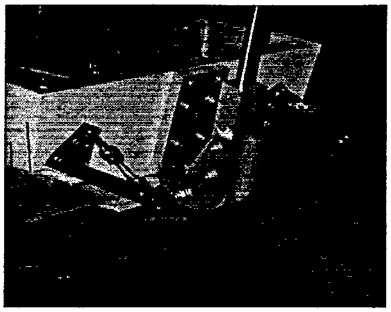


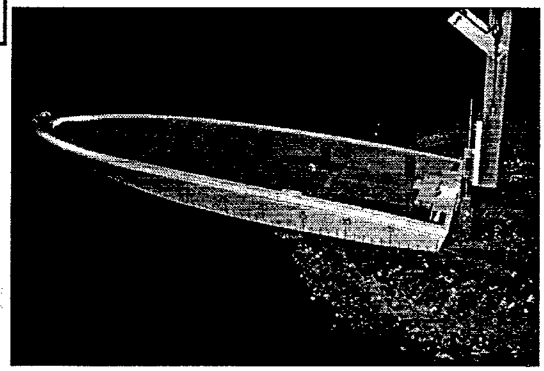


Run #	Time from Prev. Run minutes	Ave V ft/sec	Trim Tab Deflection deg, + dn	Running Trim deg, + up	Rod Trim Angle deg, + up	Wetted Chine inches	Wetted Keel inches	Stability Observed
147	1st Run	15.02	0	8.06	4.5	22	33	Stable
148	5.65	17.52	0	7.26	4.5	18	33	Inception
149	8.31	17.52	4	7.22	4.5	18	33	Stable
150	6.67	20.03	4	5.46	4.5	?	?	Porpoise
151	7.71	20.03	14	4.78	4.5	?	?	Porpoise
152	6.73	20.02	16	4.45	4.5	15	39	Inception
153	10.55	20.03	16	4.41	4.5	14	40	Stable
154	5.85	24.03	16	3.16	4.5	?	?	Porpoise
155	7.65	24.04	18	2.86	4.5	18	45	Inception
156	9.03	27.02	18	2.12	4.5	19	50	Porpoise
157	8.25	27.03	14	2.76	4.5	?	?	Porpoise
158	5.85	27.03	16	2.79	4.5	19	?	Porpoise
159	5.36	30.03	16	?	4.5	?	?	Porpoise
160	7.45	30.03	18	1.87	4.5	?	?	Inception
161	6.13	30.03	19	1.56	4.5	22	50	Stable
162	6.07	32.03	19	1.27	4.5	25	50	Stable
163	9.17	32.03	17	1.67	4.5	23	50	Stable
164	6.73	32.03	15	1.89	4.5	18	50	Inception
165	6.37	32.04	13	2.14	4.5	?	?	Porpoise

Run #	Δ lb	CDelta	Calc Tab Lift	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
147	55.98	0.532	0.00	0.532	18.02	4.37	17.43	2.70	2.43	0.181
148	55.98	0.532	0.00	0.532	18.02	4.37	17.43	3.15	2.83	0.133
149	55.98	0.532	1.05	0.522	18.02	4.37	17.43	3.15	2.83	0.133
150	55.98	0.532	1.37	0.519	18.02	4.37	17.43	3.60	3.24	0.102
151	55.98	0.532	4.81	0.487	18.02	4.37	17.43	3.60	3.24	0.102
152	55.98	0.532	5.49	0.480	18.02	4.37	17.43	3.59	3.24	0.102
153	55.98	0.532	5.49	0.480	18.02	4.37	17.43	3.60	3.24	0.102
154	55.98	0.532	7.91	0.457	18.02	4.37	17.43	4.31	3.88	0.071
155	55.98	0.532	8.90	0.448	18.02	4.37	17.43	4.32	3.89	0.071
156	55.98	0.532	11.25	0.425	18.02	4.37	17.43	4.85	4.37	0.056
157	55.98	0.532	8.76	0.449	18.02	4.37	17.43	4.85	4.37	0.056
158	55.98	0.532	10.01	0.437	18.02	4.37	17.43	4.85	4.37	0.056
159	55.98	0.532	12.35	0.415	18.02	4.37	17.43	5.39	4.85	0.045
160	55.98	0.532	13.89	0.400	18.02	4.37	17.43	5.39	4.85	0.045
161	55.98	0.532	14.67	0.393	18.02	4.37	17.43	5.39	4.85	0.045
162	55.98	0.532	16.68	0.374	18.02	4.37	17.43	5.75	5.18	0.040
163	55.98	0.532	14.93	0.390	18.02	4.37	17.43	5.75	5.18	0.040
164	55.98	0.532	13.17	0.407	18.02	4.37	17.43	5.75	5.18	0.040
165	55.98	0.532	11.42	0.424	18.02	4.37	17.43	5.75	5.18	0.040

HSAC C Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 64.7 deg F

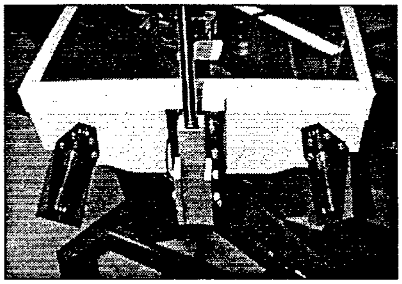


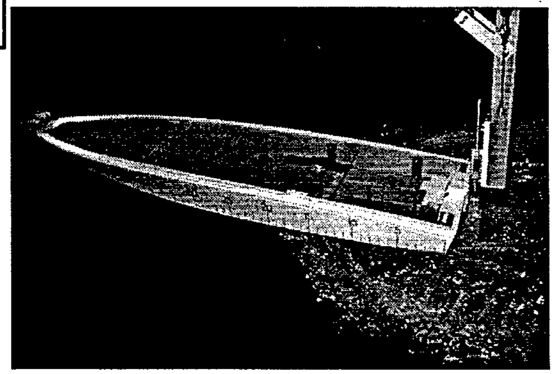


Run #	Time from Prev. Run minutes	Ave V ft/sec	Trim Tab Deflection deg, + dn	Running Trim deg, + up	Rod Trim Angle deg, + up	Wetted Chine inches	Wetted Keel inches	Stability Observed
166	1st Run	15.01	0	7.99	4.5	24	35	Stable
167	5.43	17.51	0	7.23	4.5	20	34	Inception
168	34.40	20.04	0	5.78	4.5	?	?	Porpoise
169	15.66	20.05	15	4.75	4.5	20	39	Stable
170	6.45	20.06	12	4.96	4.5	?	?	Porpoise
171	6.17	20.03	14	4.80	4.5	?	?	Inception
172	6.38	24.04	16	3.03	4.5	?	?	Porpoise
173	5.86	24.06	18	3.11	4.5	19	45	Inception
174	7.20	24.03	19	2.98	4.5	20	45	inception
175	6.05	27.02	19	2.28	4.5	20	47	Stable
176	5.90	27.02	17	2.55	4.5	?	?	Inception
177	6.63	30.02	17	2.05	4.5	?	50	Stable
178	6.37	30.03	15	2.31	4.5	?	?	Porpoise
179	7.48	32.03	15	1.89	4.5	?	?	Inception
180	5.97	32.03	16	1.87	4.5	?	?	Inception

Run #	Δ lb	CDelta	Calc Tab Lift	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
166	59.31	0.564	0.00	0.564	19.45	4.57	17.1	2.67	2.43	0.192
167	59.31	0.564	0.00	0.564	19.45	4.57	17.1	3.11	2.83	0.141
168	59.31	0.564	0.00	0.564	19.45	4.57	17.1	3.56	3.24	0.108
169	59.31	0.564	5.16	0.515	19.45	4.57	17.1	3.57	3.24	0.107
170	59.31	0.564	4.13	0.525	19.45	4.57	17.1	3.57	3.24	0.107
171	59.31	0.564	4.81	0.518	19.45	4.57	17.1	3.56	3.24	0.108
172	59.31	0.564	7.91	0.489	19.45	4.57	17.1	4.27	3.89	0.075
173	59.31	0.564	8.92	0.479	19.45	4.57	17.1	4.28	3.89	0.075
174	59.31	0.564	9.39	0.475	19.45	4.57	17.1	4.27	3.88	0.075
175	59.31	0.564	11.87	0.451	19.45	4.57	17.1	4.80	4.37	0.059
176	59.31	0.564	10.62	0.463	19.45	4.57	17.1	4.80	4.37	0.059
177	59.31	0.564	13.11	0.439	19.45	4.57	17.1	5.34	4.85	0.048
178	59.31	0.564	11.58	0.454	19.45	4.57	17.1	5.34	4.85	0.048
179	59.31	0.564	13.17	0.439	19.45	4.57	17.1	5.70	5.18	0.042
180	59.31	0.564	14.05	0.430	19.45	4.57	17.1	5.70	5.18	0.042

HSAC D Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 64.2 deg F



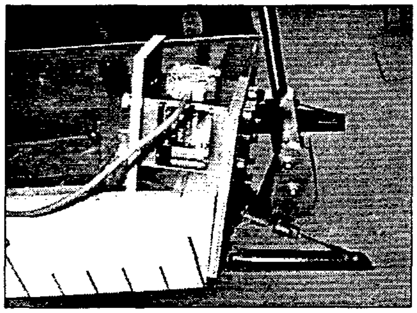


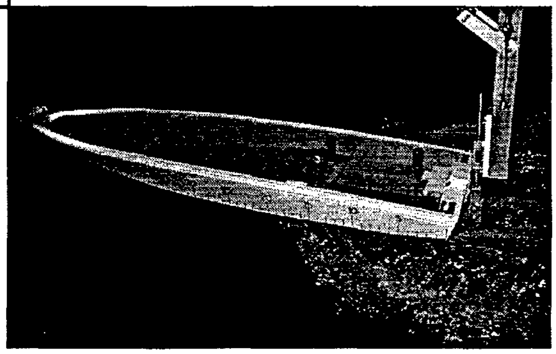
Run #	Time from Prev. Run minutes	Ave V ft/sec	Trim Tab Deflection deg, + dn	Trim Tab Area deg, + up	Running Trim deg, + up	Rod Trim Angle inches	Wetted Chine inches	Wetted Keel	Stability Observed
225	1st Run	15.00	0	8.5	8.02	4.5	?	?	Stable
226	5.53	19.94	0	8.5	5.08	4.5	?	?	Porpoise
227	7.37	20.05	5	8.5	5.05	4.5	?	?	Porpoise
228	7.63	20.01	10	8.5	4.66	4.5	?	?	Porpoise
229	7.70	20.00	15	8.5	4.01	4.5	20	43	Stable
230	34.45	20.01	19	6.375	3.91	4.5	?	?	Stable

Run #	Δ lb	CDelta	Calc Tab Lift	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
225	51.46	0.489	0.00	0.489	17.41	4.23	17.94	2.73	2.42	0.167
226	51.46	0.489	0.00	0.489	17.41	4.23	17.94	3.63	3.22	0.094
227	51.46	0.489	2.30	0.468	17.41	4.23	17.94	3.65	3.24	0.093
228	51.46	0.489	4.58	0.446	17.41	4.23	17.94	3.64	3.23	0.094
229	51.46	0.489	6.86	0.424	17.41	4.23	17.94	3.64	3.23	0.094
230	51.46	0.489	6.98	0.423	17.41	4.23	17.94	3.64	3.23	0.094

HSAC E Trim Tab Lift Test
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 56.0 deg F

Note: dCL/da is resolved perpendicular to keel

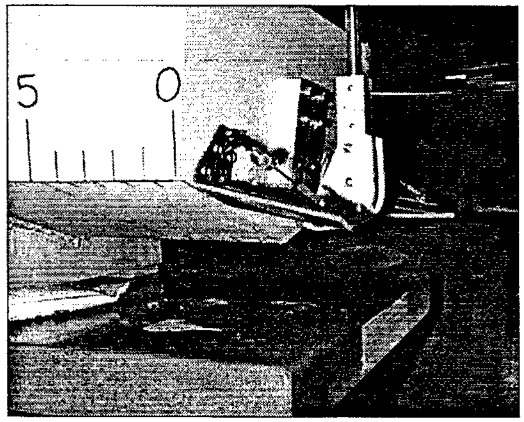




Run #	Time from Prev. Run minutes	Ave V ft/sec	Trim Tab Deflection deg, + dn	dCL/da deg, + up	Running Trim deg, + up	Rod Trim Angle inches	Wetted Chine inches	Wetted Keel	Stability Observed
231	1st Run	11.97	0		9.22	4.5	24.5	34	Stable
232	1st Run	11.97	2	0.0165	9.16	4.5	26	35	Stable
233	6.41	11.97	6	0.01275	9.06	4.5	26	36	Stable
234	6.77	17.45	0		6.54	4.5	?	?	Porpoise
235	5.60	17.45	4	0.0067	6.45	4.5	?	?	Porpoise
236	6.68	17.45	8	0.00952	6.13	4.5	?	?	Porpoise
237	6.85	17.45	12	0.00941	5.74	4.5	?	?	Stable
238	5.42	17.45	16	0.0105	5.26	4.5	?	?	Stable
239	5.42	26.9	16	0.0101	2.31	4.5	?	?	Porpoise
240	6.85	26.92	12	0.0101	3.12	4.5	?	?	Porpoise
241	9.40	23.94	12	0.0103	3.40	4.5	?	?	Porpoise
242	5.02	23.92	16	0.00969	2.98	4.5	?	?	Inception
243	5.53	29.9	16	0.00969	2.07	4.5	?	?	Porpoise
244	7.60	29.9	16	0.00949	2.21	4.5	?	?	Stable
245	5.35	29.9	14	0.01001	2.28	4.5	?	?	Porpoise
246	5.78	29.9	12	0.0098	2.47	4.5	?	?	Porpoise
247	6.21	29.9	10	0.0095	2.88	4.5	?	?	Popoise

Run #	Δ lb	CDelta	Calc Tab Lift	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
231	48.35	0.460	0.00	0.460	17.59	4.68	18.89	2.20	1.93	0.246
232	48.35	0.460	0.25	0.457	17.59	4.68	18.89	2.20	1.93	0.246
233	48.35	0.460	0.74	0.453	17.59	4.68	18.89	2.20	1.93	0.246
234	48.35	0.460	0.00	0.460	17.59	4.68	18.89	3.21	2.82	0.116
235	48.35	0.460	1.04	0.450	17.59	4.68	18.89	3.21	2.82	0.116
236	48.35	0.460	2.09	0.440	17.59	4.68	18.89	3.21	2.82	0.116
237	48.35	0.460	3.13	0.430	17.59	4.68	18.89	3.21	2.82	0.116
238	48.35	0.460	4.17	0.420	17.59	4.68	18.89	3.21	2.82	0.116
239	48.35	0.460	9.91	0.366	17.59	4.68	18.89	4.95	4.35	0.049
240	48.35	0.460	7.44	0.389	17.59	4.68	18.89	4.95	4.35	0.049
241	48.35	0.460	5.89	0.404	17.59	4.68	18.89	4.40	3.87	0.061
242	48.35	0.460	7.84	0.385	17.59	4.68	18.89	4.40	3.87	0.062
243	48.35	0.460	12.24	0.343	17.59	4.68	18.89	5.50	4.83	0.039
244	53.51	0.509	12.24	0.392	19.27	5.05	18.71	5.41	4.83	0.044
245	53.51	0.509	10.71	0.407	19.27	5.05	18.71	5.41	4.83	0.044
246	53.51	0.509	9.18	0.422	19.27	5.05	18.71	5.41	4.83	0.044
247	53.51	0.509	7.65	0.436	19.27	5.05	18.71	5.41	4.83	0.044

PCC A Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 64.5 deg F



Run #	Time from Prev. Run minutes	Ave V ft/sec	Trim Tab Deflection deg, + dn	Trim Tab Area deg, + up	Trim Tab Config deg, + up	Running Trim inches	Rod Trim Angle inches	Wetted Chine	Wetted Keel	Stability Observed
181	1st Run	14.01	0	6.375	Bare	8.37	4.5	19.5	30	Stable
182	10.98	16.02	0	6.375	Bare	7.00	4.5	?	?	Porpoise
183	7.20	16.02	14	6.375	Bare	5.95	4.5	19	34	Inception
184	5.28	20.03	14	6.375	Bare	4.11	4.5	?	?	Porpoise
185	5.88	20.03	17	6.375	Bare	3.73	4.5	17	37	Stable
186	5.68	20.04	15	6.375	Bare	3.97	4.5	17	37	Inception
187	5.00	24.07	15	6.375	Bare	2.76	4.5	15	41	Inception
188	5.55	24.12	17	6.375	Bare	2.34	4.5	15	43	Stable
189	7.97	27.04	15	6.375	Bare	2.25	4.5	13	43	Inception
190	6.31	27.03	13	6.375	Bare	2.53	4.5	?	?	Porpoise
191	5.58	27.03	17	6.375	Bare	1.96	4.5	14	44	Stable
192	5.96	30.03	15	6.375	Bare	1.86	4.5	12	44	Stable
193	8.16	30.03	13	6.375	Bare	2.15	4.5	13	43	Inception
194	5.48	30.04	11	6.375	Bare	2.31	4.5		?	Porpoise
195	6.03	32.04	11	6.375	Bare	1.99	4.5	8	?	Inception
196	6.38	32.03	11	6.375	Bare	2.10	4.5	8	43	Inception
197	6.62	32.03	13	6.375	Bare	1.83	4.5	8	43	Stable
198	1st Run	14.01	0	6.375	Insert A	8.81	4.5	20	35	Inception
199	5.30	16.01	0	6.375	Insert A	6.99	4.5	?	?	Porpoise
200	8.67	16.01	14	6.375	Insert A	5.76	4.5	20	35	Stable
201	6.62	16.01	12	6.375	Insert A	6.04	4.5	19	34	Inception
202	5.60	20.03	12	6.375	Insert A	4.04	4.5	?	?	Porpoise
203	7.27	20.02	15	6.375	Insert A	3.87	4.5	?	16.5	Inception
204	5.90	20.02	16	6.375	Insert A	3.67	4.5	18	40	Stable
205	8.17	24.14	16	6.375	Insert A	2.35	4.5	15	43	Stable
206	6.87	24.04	14	6.375	Insert A	2.90	4.5	14	40	Stable
207	7.23	24.11	12	6.375	Insert A	2.96	4.5	?	?	Inception
208	5.67	27.03	12	6.375	Insert A	2.42	4.5	13	45	Inceptoin
209	5.63	27.03	14	6.375	Insert A	2.15	4.5	13	43	Stable
210	6.25	30.03	13	6.375	Insert A	1.85	4.5	11	43	Stable
211	5.7	30.02	11	6.375	Insert A	2.12	4.5	10	42	Inception
212	7.8	30.03	9	6.375	Insert A	2.28	4.5	?	?	Porpoise
213	5.35	32.01	9	6.375	Insert A	2.16	4.5	9	?	Inception
214	5.72	32.02	10	6.375	Insert A	1.92	4.5	9	?	Inception
215	1st Run	20.01	9	8.5	Insert B	4.57	4.5	15	37	Inception
216	5.83	24.02	9	8.5	Insert B	3.15	4.5	7	?	Porpoise
217	5.53	24.05	11	8.5	Insert B	3	4.5	15	43	Inception
218	4.87	27.01	11	8.5	Insert B	2.39	4.5	14	43	Stable
219	5.55	27.02	9	8.5	Insert B	2.65	4.5	?	?	Porpoise
220	6.83	29.99	9	8.5	Insert B	2.39	4.5	10	44	Inception
221	12.96	30	7	8.5	Insert B	2.69	4.5	10	42	Stable
222	5.65	29.99	5	8.5	Insert B	2.56	4.5	?	?	Porpoise
223	4.95	32.02	5	8.5	Insert B	2.31	4.5	?	?	Porpoise
224	5.78	31.98	7	8.5	Insert B	2.15	4.5	?	?	Stable

PCC A Porpoising Test.
Tow Point = 1.0" abl, -1' wrt ap
Fresh Water, 64.5 deg F

Run #	Δ lb	CDelta	Calc Tab Lift	Cdelta	LCG in fwd ap	VCG in abl	K in	VolFn	Cv	CL
181	54.8	0.400	0.00	0.400	17.01	4.37	14.29	2.52	2.17	0.170
182	54.8	0.400	0.00	0.400	17.01	4.37	14.29	2.89	2.48	0.130
183	54.8	0.400	3.08	0.377	17.01	4.37	14.29	2.89	2.48	0.130
184	54.8	0.400	4.82	0.365	17.01	4.37	14.29	3.61	3.10	0.083
185	54.8	0.400	5.85	0.357	17.01	4.37	14.29	3.61	3.10	0.083
186	54.8	0.400	5.16	0.362	17.01	4.37	14.29	3.61	3.10	0.083
187	54.8	0.400	7.45	0.345	17.01	4.37	14.29	4.34	3.72	0.058
188	54.8	0.400	8.48	0.338	17.01	4.37	14.29	4.35	3.73	0.057
189	54.8	0.400	9.40	0.331	17.01	4.37	14.29	4.87	4.18	0.046
190	54.8	0.400	8.14	0.340	17.01	4.37	14.29	4.87	4.18	0.046
191	54.8	0.400	10.65	0.322	17.01	4.37	14.29	4.87	4.18	0.046
192	54.8	0.400	11.60	0.315	17.01	4.37	14.29	5.41	4.64	0.037
193	54.8	0.400	10.05	0.326	17.01	4.37	14.29	5.41	4.64	0.037
194	54.8	0.400	8.51	0.338	17.01	4.37	14.29	5.41	4.65	0.037
195	54.8	0.400	9.68	0.329	17.01	4.37	14.29	5.77	4.95	0.033
196	54.8	0.400	9.67	0.329	17.01	4.37	14.29	5.77	4.95	0.033
197	54.8	0.400	11.43	0.316	17.01	4.37	14.29	5.77	4.95	0.033
198	54.8	0.400	0.00	0.400	17.01	4.37	14.29	2.52	2.17	0.170
199	54.8	0.400	0.00	0.400	17.01	4.37	14.29	2.88	2.48	0.130
200	54.8	0.400	3.29	0.376	17.01	4.37	14.29	2.88	2.48	0.130
201	54.8	0.400	2.82	0.379	17.01	4.37	14.29	2.88	2.48	0.130
202	54.8	0.400	4.42	0.368	17.01	4.37	14.29	3.61	3.10	0.083
203	54.8	0.400	5.51	0.360	17.01	4.37	14.29	3.61	3.10	0.083
204	54.8	0.400	5.88	0.357	17.01	4.37	14.29	3.61	3.10	0.083
205	54.8	0.400	8.55	0.337	17.01	4.37	14.29	4.35	3.73	0.057
206	54.8	0.400	7.42	0.346	17.01	4.37	14.29	4.33	3.72	0.058
207	54.8	0.400	6.40	0.353	17.01	4.37	14.29	4.34	3.73	0.058
208	54.8	0.400	8.04	0.341	17.01	4.37	14.29	4.87	4.18	0.046
209	54.8	0.400	9.38	0.331	17.01	4.37	14.29	4.87	4.18	0.046
210	54.8	0.400	10.75	0.321	17.01	4.37	14.29	5.41	4.64	0.037
211	54.8	0.400	9.09	0.333	17.01	4.37	14.29	5.41	4.64	0.037
212	54.8	0.400	7.45	0.345	17.01	4.37	14.29	5.41	4.64	0.037
213	54.8	0.400	8.46	0.338	17.01	4.37	14.29	5.77	4.95	0.033
214	54.8	0.400	9.41	0.331	17.01	4.37	14.29	5.77	4.95	0.033
215	54.8	0.400	4.41	0.368	17.01	4.37	14.29	3.61	3.09	0.084
216	54.8	0.400	6.35	0.353	17.01	4.37	14.29	4.33	3.71	0.058
217	54.8	0.400	7.78	0.343	17.01	4.37	14.29	4.33	3.72	0.058
218	54.8	0.400	9.82	0.328	17.01	4.37	14.29	4.87	4.18	0.046
219	54.8	0.400	8.04	0.341	17.01	4.37	14.29	4.87	4.18	0.046
220	54.8	0.400	9.90	0.328	17.01	4.37	14.29	5.40	4.64	0.037
221	54.8	0.400	7.71	0.344	17.01	4.37	14.29	5.41	4.64	0.037
222	54.8	0.400	5.50	0.360	17.01	4.37	14.29	5.40	4.64	0.037
223	54.8	0.400	6.27	0.354	17.01	4.37	14.29	5.77	4.95	0.033
224	54.8	0.400	8.76	0.336	17.01	4.37	14.29	5.76	4.95	0.033

Appendix B

Dynamometry Calibration Curves

NAHL Calibration of: Resistance Force Block 09/17/97
Least Squares Fit of Calibration Data
Full Scale Gage Capacity (FS): 500 lb

U.S. Naval Academy
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

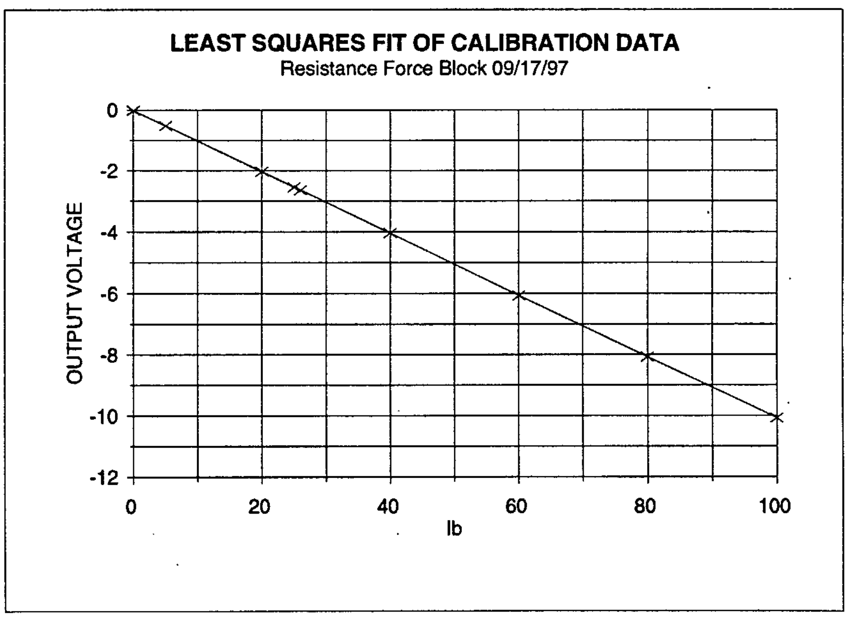
Applied Load lb	Gage Output volts	Fit Output volts	Difference lb	Percent Full Scale
0.00	-0.008	-0.01	0.0429	0.009
20.00	-2.020	-2.02	0.0387	0.008
40.00	-4.030	-4.04	0.0543	0.011
60.00	-6.050	-6.05	-0.0295	-0.006
80.00	-8.060	-8.06	-0.0139	-0.003
100.00	-10.070	-10.07	0.0017	0.000
0.00	-0.017	-0.01	-0.0466	-0.009
5.00	-0.520	-0.52	-0.0476	-0.010
25.00	-2.530	-2.53	-0.0320	-0.006
26.00	-2.630	-2.63	-0.0263	-0.005

Gage No.	HI-4-500-01
Amp No.	110955
Cable ID	
Gage Cal	8.471 V@ 5mv/v
Cal Pot	7.59 w/ 2.5mv/v

Gage Sensitivity: **-0.1006 volts / lb**
-9.9425 lb / volt

Calibration Linearity Statistics:

Max Deviation: **0.011 % Full Scale**
Max Deviation: 0.054 lb
Std. Deviation: 0.0363 lb



NAHL Calibration of: Trim Inclinometer 1/15/98
Least Squares Fit of Calibration Data
Full Scale Gage Capacity (FS): 14.5 deg

U.S. Naval Academy
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

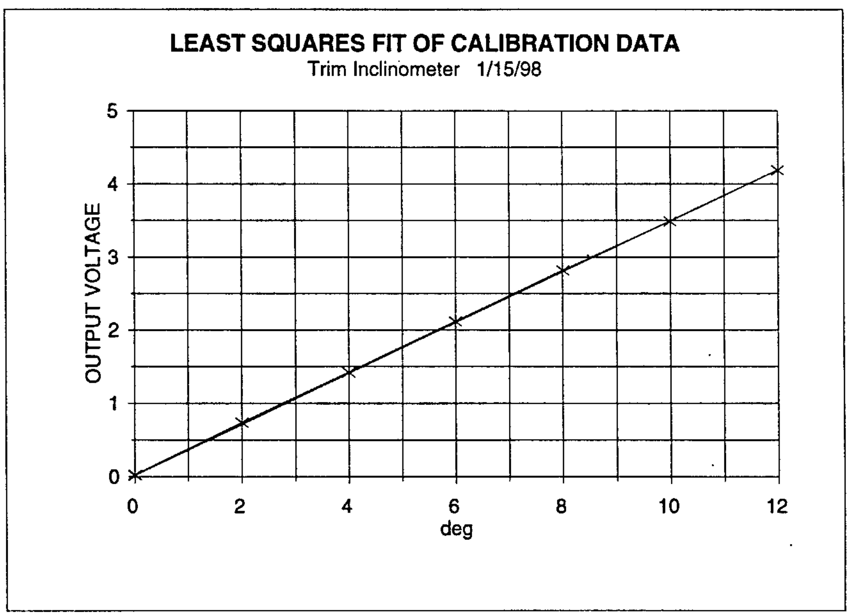
Applied Load deg	Gage Output volts	Fit Output volts	Difference deg	Percent Full Scale
0.00	0.026	0.03	0.0172	0.119
2.00	0.740	0.73	-0.0405	-0.280
4.00	1.426	1.42	-0.0176	-0.121
6.00	2.120	2.11	-0.0177	-0.122
8.00	2.820	2.81	-0.0351	-0.242
10.00	3.490	3.50	0.0340	0.234
12.00	4.190	4.20	0.0166	0.114
0.00	0.017	0.03	0.0432	0.298

Gage No.	LSOC-14.5/14572
Amp No.	003, no filter
Cable ID	
Gage Cal	
Cal Pot	

Gage Sensitivity: **0.3470 volts / deg**
2.8820 deg / volt

Calibration Linearity Statistics:

Max Deviation: 0.298 % Full Scale
Max Deviation: 0.043 deg
Std. Deviation: 0.0298 deg



NAHL Calibration of: Trim Tab Lift 1/15/98
Least Squares Fit of Calibration Data
Full Scale Gage Capacity (FS): 10 lb

U.S. Naval Academy
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

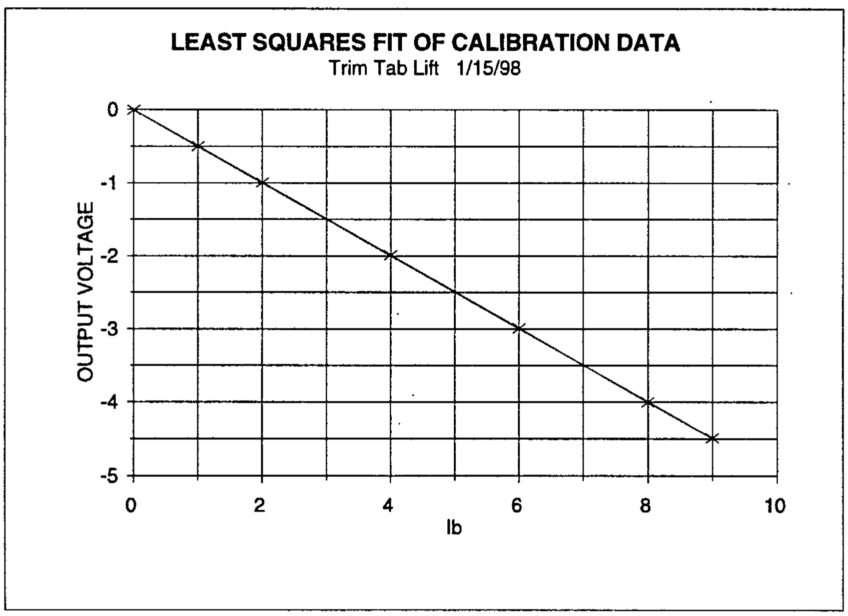
Applied Load lb	Gage Output volts	Fit Output volts	Difference lb	Percent Full Scale
0.00	-0.001	0.00	-0.0087	-0.087
1.00	-0.494	-0.50	0.0032	0.032
2.00	-0.990	-0.99	0.0091	0.091
4.00	-1.984	-1.99	0.0167	0.167
6.00	-2.986	-2.99	0.0084	0.084
8.00	-4.000	-3.99	-0.0240	-0.240
9.00	-4.484	-4.49	0.0059	0.059
0.00	-0.002	0.00	-0.0107	-0.107

Gage No.	HI-2-10-01
Amp No.	Val 2
Cable ID	
Gage Cal	6.892@5mv/v
Cal Pot	7.59 w/ 2.5mv/v

Gage Sensitivity: **-0.4989 volts / lb**
-2.0043 lb / volt

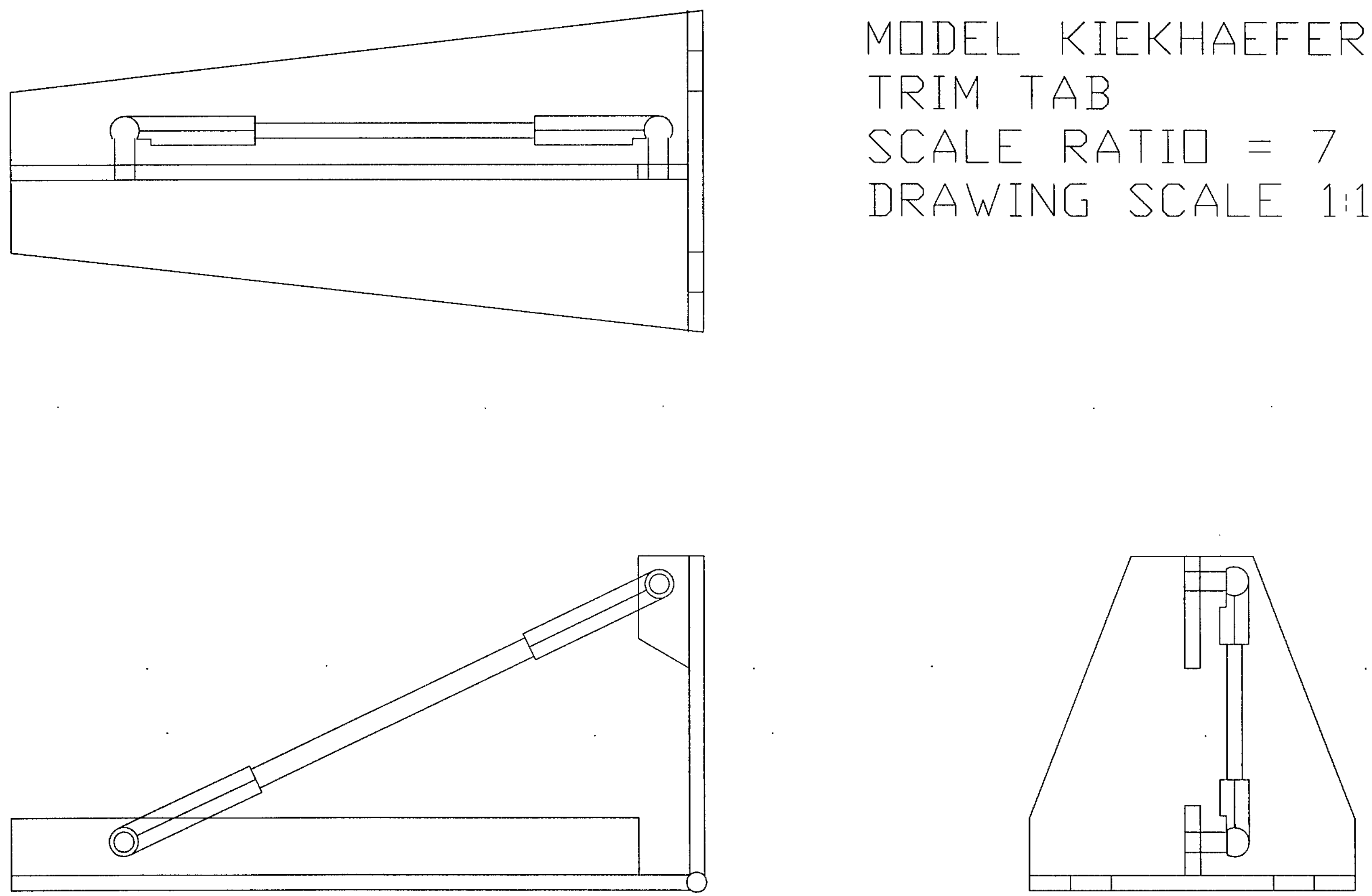
Calibration Linearity Statistics:

Max Deviation: 0.240 % Full Scale
Max Deviation: 0.024 lb
Std. Deviation: 0.0125 lb



Appendix C

Trim Tab Design and Calibration

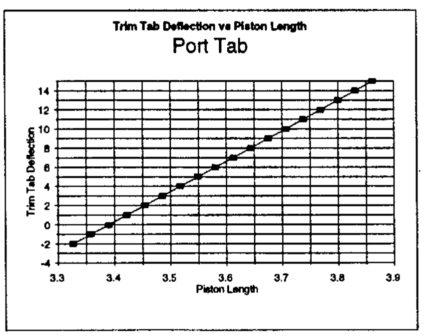

MODEL KIEKHAEFER
TRIM TAB
SCALE RATIO = 7
DRAWING SCALE 1:1

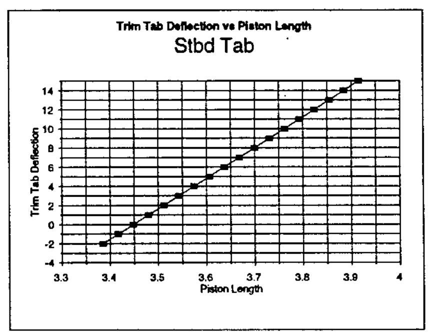
HSAC MKII Trim Tab Deflection Regression

			Piston Coordinates			
L=	4.25	in	Port Tab		Stbd Tab	
Broot=	2	in				
Btip=	1	in	x1	0.297	x1	0.242
A=	6.375	in	y1	1.807	y1	1.806
Centroid	1.806	in	x2	3.78	x2	3.77
			y2	0.287	y2	0.257
Boat						
				14.4417		14.8462
Tramsom	15	deg wrt vert		3.80022		3.85307
Warp	-2	deg wrt BL				

Angles Solved Graphically using AUTOCAD LT

Port Tab Flow Angle	Deflection	Piston	Stbd Tab Flow Angle	Deflection	Piston
15	2	3.8619	15	2	3.9151
14	1	3.8311	14	1	3.8848
13	0	3.8002	13	0	3.8543
12	-1	3.7692	12	-1	3.8237
11	-2	3.738	11	-2	3.7929
10	-3	3.7068	10	-3	3.762
9	-4	3.6754	9	-4	3.7311
8	-5	3.644	8	-5	3.7
7	-6	3.6124	7	-6	3.6688
6	-7	3.5808	6	-7	3.6375
5	-8	3.5491	5	-8	3.6061
4	-9	3.5173	4	-9	3.5747
3	-10	3.4855	3	-10	3.5431
2	-11	3.4537	2	-11	3.5116
1	-12	3.4218	1	-12	3.4799
0	-13	3.3899	0	-13	3.4482
-1	-14	3.3579	-1	-14	3.4165
-2	-15	3.326	-2	-15	3.3847





Port Tab Regression Output:			Stbd Tab Regression Output:		
Constant		3.39049	Constant		3.44895
Std Err of Y Est		0.00095	Std Err of Y Est		0.00115
R Squared		0.99997	R Squared		0.99996
No. of Observations		18	No. of Observations		18
Degrees of Freedom		16	Degrees of Freedom		16
X Coefficient(s)	0.03156		X Coefficient(s)	0.03123	
Std Err of Coef.	4.3E-05		Std Err of Coef.	5.2E-05	

Piston Length = 3.3905 + .0316 * Tab Deflection

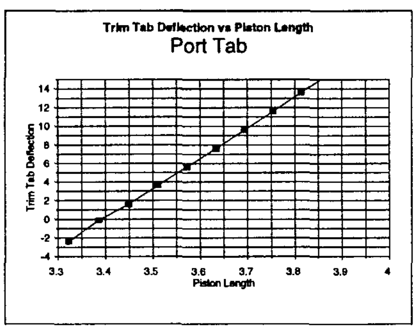
Piston Length = 3.449 + .0312 * Tab Deflection

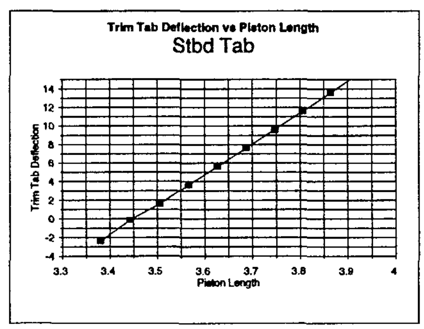
42' PCC Trim Tab Deflection Regression

		Piston Coordinates				
L=	4.25 in	Port Tab			Stbd Tab	
Broot=	2 in					
Btip=	1 in	x1	0.297		x1	0.242
A=	6.375 in	y1	1.807		y1	1.806
Centroid	1.806 in	x2	3.53		x2	3.52
		y2	0.287		y2	0.257
Boat						
			14.4417			14.8462
Tramsom:	5.1 deg wrt vert		3.80022			3.85307
Warp	0 deg wrt BL					

Angles Solved Graphically using AUTOCAD LT

Port Tab Flow Angle	Deflection	Piston	Stbd Tab Flow Angle	Deflection	Piston
17.6	2	3.9304	17.6	2	3.9786
15.6	1	3.8725	15.6	1	3.9218
13.6	0	3.8138	13.6	0	3.8642
11.6	-1	3.7544	11.6	-1	3.8059
9.6	-2	3.6944	9.6	-2	3.7468
7.6	-3	3.6337	7.6	-3	3.6871
5.6	-4	3.5725	5.6	-4	3.6268
3.6	-5	3.5105	3.6	-5	3.566
1.6	-6	3.4485	1.6	-6	3.5046
-0.1	-7	3.3859	-0.1	-7	3.4427
-2.4	-8	3.3229	-2.4	-8	3.3804





Regression Output: (Port Tab)

Constant		3.39772
Std Err of Y Est		0.00427
R Squared		0.9996
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	0.03057	
Std Err of Coef.	0.0002	

Piston Length = 3.3977 + .03057 * Tab Deflection

Regression Output: (Stbd Tab)

Constant		3.45454
Std Err of Y Est		0.00443
R Squared		0.99955
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	0.03009	
Std Err of Coef.	0.00021	

Piston Length = 3.4545 + .03009 * Tab Deflection

Appendix D

Iterative Solution Method Programming Details

Spreadsheet Solution Routine

Described here is the program used to program Excel 97 to perform this analysis. The method may be programmed into any brand of spreadsheet, provided it is capable of executing programmable Macro type functions, and the appropriate conversions can be made. The regression for average bottom velocity was performed based on the graphs provided in Savitsky's '64 paper. This version does not contain any provision for estimating the effective deadrise angle of hulls with lifting strakes. It will work for featureless hulls, and for hulls with strakes provided the effective deadrise angle for the given loading condition is entered into the "deadrise" block. Many of the IF() statements seen were used to prevent the equations from going too far out of range when drastic changes were made to the inputs, such as greatly increasing or decreasing the scale of hull being entered. The Reset Macro described brings the program to a reasonable starting point for iteration.

Preparing the spreadsheet:

Set up the workbook with five worksheets, data input, critical trim angle calculation, general calculation, reset macro page, and one for automatic data assembly. Cell addresses with no page designation refer to the current page. Square brackets [] indicate cell inputs.

"Main" Worksheet

B7	L_{BP} [input]
B8	B_{PX} [input]
B9	β, Deadrise, degrees [input]
B10	Δ, lb. [input]
B11	Water selection (1=salt, 0=fresh) [input]
F6	LCG, ft forward transom (+ forward) [input]
F7	VCG, ft abl. [input]
F8	Vertical thrust point, ft abl. [input]
F9	Propeller setback, ft aft transom (+ aft) [input]
F10	Thrust line angle, deg wrt bl. [input]
J6	Trim tab chord, ft. [input]
J7	Trim tab root span, ft. [input]
J8	Trim tab tip span, ft. [input]
J9	Trim tab deflection, deg. [input]

"Trim" Worksheet

B2	C_{Δ} [=Main!$B$10/Main!$B$8^3/$B$3]
B3	Water Density [=IF(Main!B11=1,64,62.4)]
B4	β [=Main!B9]

Following are iterative steps. The following cells were copied down using a C_V resolution of 0.25 in the A column. C_V values below 2 are not useful and were not used for calculations.

A17 C_v [input]

B17 V, ft/sec [=A17*SQRT(32.17*Main!$B$8)]

C17 V, knots [=B17/1.689]

D17 Critical Trim [=0.1197*Main!$B$9^0.7651*EXP(15.71*E17*Main!$B$9^-0.2629)]

E17 $\sqrt{(C_L/2)}$ [=SQRT($B$2/A17^2)]

F17 C_δ [=(Main!$B$10-Calculation!GC8)/$B$3/Main!$B$8^3]

G17 Corrected Trim [=0.1197*Main!$B$9^0.7651*EXP(15.71*SQRT(F17)/A17 *Main!$B$9^-0.2629)]

H17 Thrust angle [=Main!$F$10-Trim!G17]

"Calculation" Worksheet

I1 C_Δ [=Trim!B2]

K1 ρ [=IF(Main!B11=1,1.9905,1.9365)]

K2 ν [=IF(Main!B11=1,0.00001225,0.0000115)]

V1 Trim Tab AR [=(Main!J7-0.25*(Main!J7-Main!J8))/Main!J6]

V2 Lift Curve Slope [=PI()*V1/2/57.3*COS(RADIANS(Main!B9))]

As in "Trim" the following were copied down at a C_V resolution of 0.25. Cell E8 serves as the reference point for calculations. It was set at a reasonable value simply to make sure the formulas were entered correctly. The program uses that cell to iterate.

A8 C_V [=Trim!A17]

B8 V, ft/sec [=Trim!B17]

C8 V, knots [=B8/1.689]

D8 Crit Trim [=Trim!G17]

E8 Keel Planing Depth, ft. [input]

F8 L_K [=E8/SIN(D8*PI()/180)]

G8 L_C [=F8-Main!$B$8*TAN(Main!$B$34*PI()/180)/PI()/ TAN(Calculation!D8*PI()/180)]

H8 λ [=(F8+G8)/2/Main!$B$8]

I8 C_{Lo} [=D8^1.1*(0.012*H8^0.5+(0.0055*H8^2.5)/A8^2)]

J8 $C_{L\beta}$ [=I8-0.0065*Main!$B$9*Calculation!I8^0.6]

K8 Planing lift [=IF($K$1/2*B8^2*Main!$B$8^2*J8<0,0.1,$K$1/2*B8^2* Main!$B$8^2*J8)]

L8 Force Error [=(K8)*COS(RADIANS(D8))-Main!$B$10+S8 *SIN(RADIANS(D8+Trim!M17))-O8*SIN(RADIANS(D8))+V8 *COS(RADIANS(D8))]

M8 C_f ITTC [=0.075/(LOG(B8*N8*H8*Main!$B$8/$K$2)-2)^2]

N8 V_1/V [=((1.005347+0.0004065*Main!$B$9)+(-0.01004+0.000119*Main!$B$9)*D8)* H8^((-0.005613+0.000069*Main!$B$9)+(0.004536+-0.0000725*Main!$B$9)* D8)]

O8 Viscous Drag [=M8*$K$1*(B8*N8)^2*(H8*Main!$B$8^2+G8*(E8-Main!$B$8/2*TAN(Main!$B$9*PI()/180)))/2/COS(Main!$B$9*PI()/180)]

P8 ΔTan(τ) [=K8*TAN(RADIANS(D8))]

Q8 Total Drag [=O8/COS(D8*PI()/180)+P8+V8/COS(RADIANS(Main!$J$10))*SIN(RADIANS(Calculation!D8+Main!$J$10))]

R8 EHP [=Q8*B8/550]

S8 Required T [=Q8/COS(RADIANS(D8+Trim!M17))]

T8 THP [=S8*B8/550]

U8 Thrust Moment [=S8*COS(RADIANS(Trim!M17))*(Main!$F$7-Main!$F$8)-S8*SIN(RADIANS(Trim!M17))*(Main!$F$6+Main!$F$9)]

V8 Trim Tab Lift [=0.5*$K$1*B8^2*Main!$J$6*0.5*(Main!$J$7+Main!$J$8)*$V$2*2*(Main!$J$10)

W8 Tab Moment [=-V8*(Main!$F$6+Main!$J$6*0.25)-V8*(Main!$F$7-Main!$B$8/2/COS(RADIANS(Main!$J$10))*SIN(RADIANS(Main!$J$10)))]

X8 L_P [=(0.75-1/(5.21*Calculation!A8^2/Calculation!H8^2+2.39))*Calculation!H8*Main!$B$8]

Y8 N Moment [=(X8-Main!$F$6)*K8]

Z8 D_f Moment [=O8*(Main!$F$7-Main!$B$8/4*TAN(Main!$B$9*PI()/180))]

AA8 Σ Moments [=U8+W8+Y8+Z8]

AB8 Req'd Moment [=IF(AA8<0,0,-AA8)]

The next columns automatically select the critical points from the stability curves the "blank" terms were used to prevent Excel from recognizing a number in those cells.

First Row:

AC8 [=IF(AB8=0,"blank",AB8)]

AD8 [=AC8]

AE8 [=IF(AD8="blank",0,C8)]

AF8 [=IF(AB9=0,AC8,"blank")]

AG8 [=IF(AF8="blank",0,C8)]

Second Row, copied down to the last row

AC9 [=IF(AB9=0,"blank",AB9)]

AD9 [=IF(AB8=0,AC9,"blank")]

AE9 [=IF(AD9="blank",0,C9)]

AF9 [=IF(AB10=0,AC9,"blank")]

AG9 [=IF(AF9="blank",0,C9)]

Summing Cells. These collect the critical points for each iteration of trim tab deflection.

AD42 [=Main!J10]

AE42 [=MAX(AE8:AE40)]

AF42 [=AD42]

AG42 [=MAX(AG8:AG40)]

"Reset" Worksheet. This formula was copied down to match the number of rows of the "Calculation" worksheet. It sets the planing depth to beam/4 to bring the initial values in range.

A8 [=Main!$B$8/4]

"Assemble" Worksheet. This was left blank. The Macro functions will fill it.

Macros: These were recorded using the recording function. Following are the VisualBasic recordings.

```
Sub Macro1()
 '
 ' Macro1 Macro
 ' Macro recorded 11/1/97 by Tullio Celano
 '
 ' Keyboard Shortcut: Ctrl+r
 '
    Sheets("Reset").Select
    Range("A8:A40").Select
    Selection.Copy
    Sheets("Calculation").Select
    Range("E8").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=False
    Sheets("Main").Select
 End Sub


Sub VertPos()
'
' VertPos Macro
' Macro recorded 10/22/97 by Tullio Celano
'
' Keyboard Shortcut: Ctrl+Shift+C
'
   Range("L8").GoalSeek Goal:=0, ChangingCell:=Range("E8")
```

This line was copied down and the cell number changed to reflect the corresponding row.

```
Sub Macro5()
'
' Macro5 Macro
' Macro recorded 10/22/97 by Tullio Celano
'
' Keyboard Shortcut: Ctrl+Shift+D
'
    Sheets("Calculation").Select
    Application.Run "PredictiveV8.xls!VertPos"
    Sheets("Chart2").Select
End Sub
```

Macro5 brings the spreadsheet to the right starting point, regardless of what page was active, then runs the Goal Seek for the conditions set one time across the speed range.

```
Sub TabDefGrahp()
'
' TabDefGraph Macro
' Macro recorded 11/5/97 by Tullio Celano
'
' Keyboard Shortcut: Ctrl+Shift+T
'
    Sheets("Main").Select
    Range("J10").Select
    ActiveCell.FormulaR1C1 = "0"
    Range("J11").Select
    Application.Run "PredictiveV8.xls!Macro5"
    Sheets("Calculation").Select
    Range("AD42:AE42").Select
    Selection.Copy
    ActiveWindow.ScrollWorkbookTabs Position:=xlLast
    Sheets("Assemble").Select
    Range("A7").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    ActiveWindow.ScrollWorkbookTabs Position:=xlFirst
    Sheets("Calculation").Select
    Range("AF42:AG42").Select
    Application.CutCopyMode = False
    Selection.Copy
    ActiveWindow.ScrollWorkbookTabs Position:=xlLast
```

```
Sheets("Assemble").Select
ActiveWindow.LargeScroll Down:=1
Range("A47:B47").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
ActiveWindow.ScrollWorkbookTabs Position:=xlFirst
Sheets("Main").Select
```

To create the TabDefGraph macro, the entire routine above must be executed for tab deflections from 0 to the desired. The macro first sets the tab deflection for a given iteration, then runs the programs, then collects the critical porpoising points. Since with trim tabs, there may be two critical porposing speeds, the program pastes the low value beginning at the top row (A7), and the high speed value at (A47) for zero degrees tab deflection. The paste locations must be moved closer to the center on for each tab deflection in order to be graphed.

"Chart 2" is an X-Y plot, with a smoothed line with the following series:

X [Calculation!C8:C40]

Y [Calculation!AB8;AB40]

"Chart 4" is an X-Y plot, with only points activated, and a 5th order trend line faired through. The following series were used:

X [Assemble!C7:C47]

Y [Assemble!A7:A47]